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Integrated Sedimentology and Ichnology of the Jurassic Aklavik Formation, Northern Richardson Mountains and Mackenzie Delta, N.W.T.

by

Carly Rhiannon Barnett

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A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science

Department of Earth and Atmospheric Sciences

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FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **Integrated Sedimentology and Ichnology of the Jurassic Aklavik Formation, Northern Richardson Mountains and Mackenzie Delta, N.W.T.** submitted by **Carly Rhiannon Barnett** in partial fulfillment of the requirements for the degree of Master of Science.

Date: June 20, 2003

Abstract

The southeastern basin-margin of the Brooks-Mackenzie Basin include strata of the Jurassic Aklavik Formation, the upper-most unit of the Bug Creek Group. These rocks are found in the subsurface in the southwestern region of the Mackenzie Delta, Northwest Territories, and in outcrop to the west in the Richardson Mountains.

Facies identified from outcrop suggest the presence of two separate systems tracts. The more typical facies represent highstand, suggesting deposition of a prograding wave-dominated delta and associated shorefaces. A second facies association, suggestive of transgressive conditions, represents drowning and re-activation of the shoreface and deltaic deposits. Supporting this interpretation, a *Glossifungites* surface was identified, delineating a transgressive surface of erosion.

The Aklavik Formation is classified as a quartz arenite to sublitharenite, dominated by well-sorted, rounded, monocrystalline quartz grains. This high level of maturity indicates a complex history of reworking of the sediment, with sediments sourced from the craton, as well as from Paleozoic units once exposed.

Believe nothing, no matter where you read it, or who said it, no matter if I have said it, unless it agrees with your own reason and your own common sense.

-Buddha

I am only one, but I am still someone.
I cannot do everything, but I can still do something.
Just because I cannot do everything does not give me the right to do nothing.

- Martin Luther King

For my littlest sister, Hillary Rose,
who could have been anything great and beautiful that she desired,
if she had only been given the time.

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CHAPTER ONE: INTRODUCTION, BACKGROUND, AND PREVIOUS WORK

1.1 Introductory Remarks

This study was undertaken to investigate, in detail, the Upper Jurassic Aklavik Formation in the region of the northern Richardson Mountains of the Northwest Territories. The Aklavik Formation is part of a collection of five formations, which together compose the Bug Creek Group. Previous workers have examined this group, with the primary focuses including macropaleontology and regional studies of the strata. However, the Aklavik Formation as a single unit has never been studied in detail for the purposes of understanding the ichnological character and detailed depositional setting, or for petrologically evaluating the formation as a potential reservoir in the subsurface. Petro-Canada Oil and Gas Company, with partial subsidies from Devon Canada Corporation, initiated and funded this study, with the intention of getting a better understanding of the Aklavik Formation in the subsurface. With the limited well control in the southwest region of the Mackenzie Delta, where the Aklavik Formation is a possible target, it was necessary to focus on outcrop data in order to develop a detailed sedimentological model.

1.2 Previous Work

The Mesozoic rocks of the northern Richardson Mountains have been studied somewhat regularly since approximately 1946 (Poulton *et al.* 1982), predominantly by geologists from the Geological Survey of Canada. The hydrocarbon potential of these rocks has made them a great interest to petroleum exploration companies, and it is this interest that appears to have driven the investigation of these rocks. The earliest major publications include regional geological reports by Martin (1959, 1961).

Beginning in the early 1960's, the Geological Survey of Canada conducted a large-scale geological mapping project, termed Operation Porcupine, and lead by D.K. Norris. During this project, E.W. Mountjoy was responsible for Mesozoic stratigraphy (Poulton *et al.* 1982). Numerous maps and publications resulted from this undertaking, with the most recent synthesis being a compilation edited by Norris (1997).

Much of the base for the present understanding of the Jurassic stratigraphy of the northern Richardson Mountains was formed from studies conducted by Jeletzky (1958 - 1980). Poulton continued working on the Jurassic stratigraphy in this area (1978 – 1997), and it is much of this work that was important for this thesis. A detailed summary of his work in the area is presented in Poulton *et al.* (1982). Publications by Norris (1973, 1974) and Yorath and Norris (1975) contributed to the tectonic history, and Young (1973) added to the stratigraphic evolution. Regional summary papers by Young *et al.* (1976) and Balkwill *et al.* (1983) were relevant to this study, as well as Dixon (1982) for the subsurface geology of the Jurassic.

1.3 Specific Objectives

The overall goal for industry was to better understand the reservoir potential of the Aklavik Formation. The specific components of this study were threefold:

1. Reconstruction of the paleo-depositional environments, incorporating ichnology, sedimentology, and sequence stratigraphy
2. Identification and documentation of the ichnology of the Aklavik Formation
3. Petrologic analysis of outcrop samples with recognition of the diagenetic phases that may have enhanced or destroyed porosity

In previous regional studies of the Bug Creek Group, the Aklavik Formation has been defined as a "high-energy, marine shelf sandstone" (Poulton *et al.* 1982). In order for a depositional model to be useful for predicting with some degree of certainty into the subsurface, it is necessary to refine the previous knowledge of the Aklavik Formation and examine it from a detailed perspective. Documenting physical and biogenic sedimentary structures and recognizing the strata relationships with under- and overlying formations can result in a more complete and detailed depositional model for the Aklavik Formation. The application of sequence stratigraphic concepts to the model enhances its predictive power, allowing for speculation to be made regarding possible subsurface facies.

The presence of ichnofossils had been recognized in previous studies relating to the Aklavik Formation, but the specific types had not yet been identified and documented. This was therefore an important aspect of the study, since it had previously never been published. In addition, identifying the ichnological relationships would increase the understanding of conditions at the time of deposition of the Aklavik Formation. Therefore, documentation of the ichnology benefited the depositional model for this unit.

Petrographic and provenance studies of the Bug Creek Group as a whole have been previously published (see Poulton *et al.* 1982). However, data had never been collected for the purpose of understanding the Aklavik Formation as a potential reservoir. A generalized diagenetic sequence is outlined in this study, including textural and compositional descriptions. It is important to note that this petrological study sourced all of the data from outcrop samples; therefore interpretations regarding subsurface porosity may be limited.

This thesis is presented in a manner that presents these objectives clearly. Following the introductory chapter, Chapter Two includes facies observations and interpretations. Chapter Three discusses the depositional setting in detail, as well as the stratigraphic architecture of the Aklavik Formation using sequence stratigraphic concepts. The petrological study is presented in Chapter Four, and includes interpretations relating to a general diagenetic sequence for this formation. The thesis study concludes with a summary discussion in Chapter Five. Three appendices are included containing all of the data that was collected for the purpose of this study, and used for interpretations. Incorporating sedimentology and ichnology resulted in a more complete understanding of the paleo-depositional setting during the Aklavik Formation. This, combined with the outlined diagenetic sequence, enhanced the understanding of the Aklavik Formation, and should support both future industrial as well as academic pursuits.

1.4 Study Area

The Aklavik Formation is present in the subsurface in the onshore, southwest region of the Mackenzie Delta, Northwest Territories. Currently, there are 14 wells that possibly penetrate this unit (Figure 1.1), although there is some uncertainty regarding whether the Aklavik Formation is actually present in some of these wells (Dixon 1982). The subsurface was not the primary data base for this current study, and the reader is referred to Dixon (1982) for detailed discussions and stratigraphic correlations of the Aklavik Formation.

To the west of the Mackenzie Delta, the Aklavik Formation outcrops in the Richardson Mountains, which straddle the border between the Yukon and the Northwest Territories. The specific study area includes a region approximately 1395 km^2, in the northern region of these mountains (Figure 1.1).

The Aklavik Formation is the most resistant formation within the Bug Creek Group, and hence is easily recognized (Figure 1.2 A). This unit is pervasive across the study area, but is commonly preserved as veneers of rubble, a result of the arctic exposure, and is therefore not always found as outcrop adequate for measuring sections (Figure 1.2 B). The Aklavik Formation also occurs as thick cliff-forming sandstone bluffs that are precarious to maneuver around (Figure 1.2 C). Consequently, section locations were chosen not always for their pristine outcrop, but for ease in measuring and collecting data safely.

1.5 Methods

The fieldwork for this study was completed during the summer of 2001, with a brief supplemental trip to the field area during the fall of 2002. Published outcrop work by Poulton *et al.* (1982) proved to be an important asset. With limited time in the field, key localities were chosen based on Poulton's field notes. Localities were accessible best by helicopter, as many of the quality outcrops were numerous kilometers away across difficult terrain. Fifteen sections were measured in detail, with specific attention given to the ichnologic features and physical sedimentary structures observed in the rocks. Observations also included lithology, grain size (as measured using a Canstrat grain size chart), nature of contacts, lateral variability across the outcrop, and identification of trace fossils and their relative abundance. A pogo stick (or Jacob's staff) was used to measure the thickness of the outcrop, and sections generally commenced a minimum of five meters below the first prominent sandstone bed, at least where possible. For maintaining consistency, a brunton compass was used, although the structural dip throughout the area was only very slight. Samples were collected regularly for the petrology portion of this study, and the sections were thoroughly photographed.

A handheld scintillometer was used to collect gamma radiation counts at one meter intervals for most sections. Counts were recorded every two seconds, with a total of five counts collected at each measurement site. Of the five measured values, the lowest and highest counts were disregarded and the remaining three counts were averaged. These averaged values were plotted beside each corresponding drafted litholog, and connected to create a gamma ray profile representative of the outcrop. Numerous workers have reported the collection of scintillometer data from outcrop (Slatt *et al.* 1992; Davies and Elliot 1996; Frank 2002). However, within this study, the benefits were

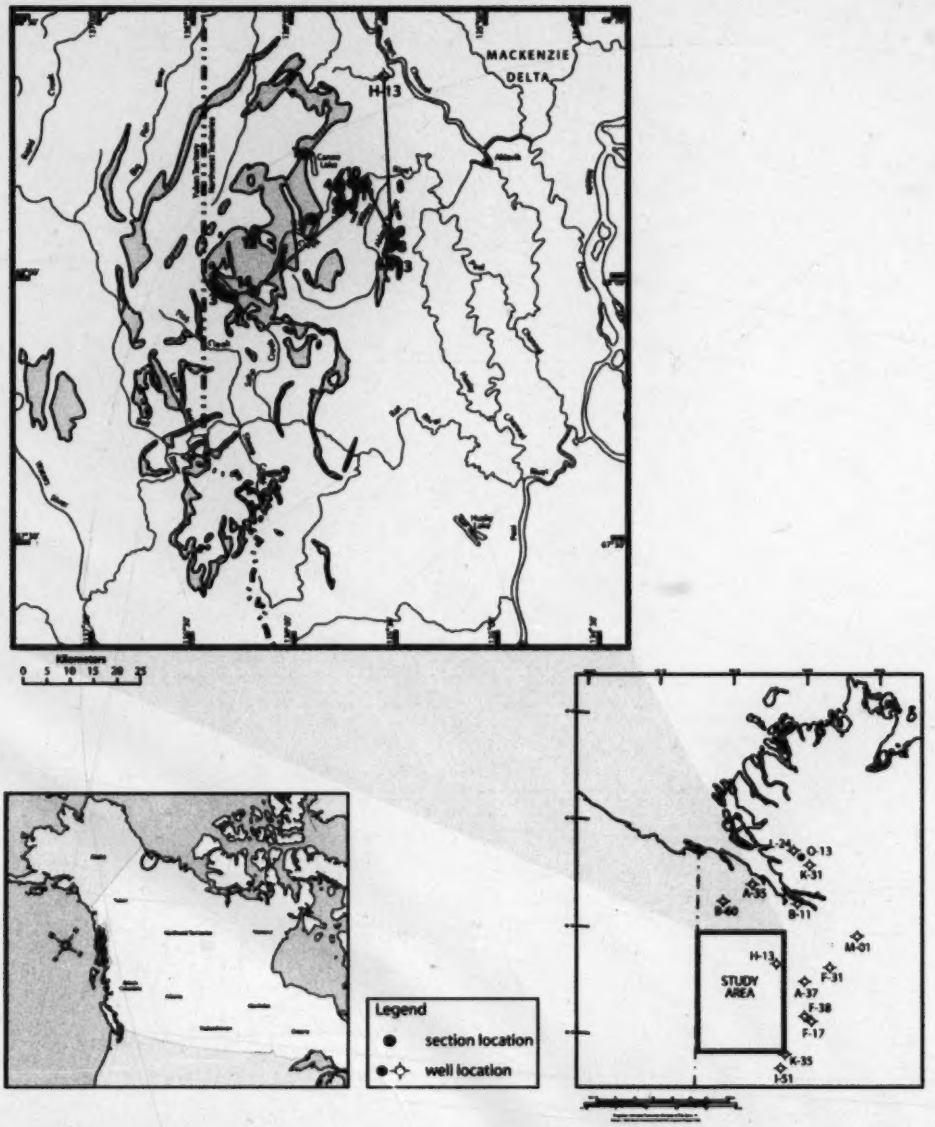


Figure 1.1 Base map for the northern Richardson Mountains, showing outcrop of Aklavik Formation (in grey) and locations of measured sections. The line of section used in Figure 3.8 is indicated as well (modified from Poulton *et al.* 1982). A map of the well locations that penetrate the Aklavik Formation is included.

Figure 1.2

A. Well preserved and exposed outcrop of the Aklavik Formation, the most resistant formation in the Bug Creek Group. Photo from the Martin Creek area.

B. Locality of poorly preserved Aklavik Formation, forming a large rubble pile. Note person in foreground for scale.

C. Cliff-forming sandstone of the Aklavik Formation. Approximately 30 m of outcrop, from the Martin Creek region.

A

B

C

not obvious as most of the outcrop measured consisted of clean quartz sandstone, rather than contrasting lithologies.

With the return from the field, measured sections were redrafted and all field notes and photographs were organized and compiled. Lithologs were created using Adobe Illustrator software. Facies were identified based on the observed features, and interpretations were made, which enabled paleo-depositional settings to be deciphered. A cross-section using the most complete sections was correlated, verifying and adding to the depositional environments interpreted for the Aklavik Formation. 115 thin sections were made in total, which were injected with blue epoxy for porosity estimation and stained with Alazarin Red S (Dickson 1965) for ease with carbonate identification. The thin sections were then analyzed, allowing for within-facies trends to be noted, as well as compositional and textural characteristics to be identified. Based on these observations, a generalized diagenetic sequence was derived for the Aklavik Formation.

1.6 Stratigraphic Nomenclature

Across the study area, the Aklavik Formation conformably and gradationally overlies the Richardson Mountains Formation (Poulton *et al.* 1982) (Figure 1.3). The Bug Creek Group as a whole sits unconformably on Permian age rocks (Norris 1973, 1974; Poulton *et al.* 1982). Overlying the Aklavik Formation is the Upper Jurassic – Lower Cretaceous Husky Formation (Poulton *et al.* 1982; Braman 1985). The Bug Creek Group as a whole is considered the southeastern equivalent of the shale of the Kingak Formation of Alaska and northern Yukon Territory (Detterman *et al.* 1975; in Poulton *et al.* 1982; Houseknecht 2001). As the rocks grade into the Kingak Formation to the west-northwest, they become an overall thicker, more argillaceous package. Therefore the Kingak Formation is considered to be a more basinward succession relative to the basin-margin facies typical of the Bug Creek Group.

Figure 1.4 summarizes the progression of the Jurassic strata from member to formation status in the region of the northern Richardson Mountains and Mackenzie Delta. The Aklavik Formation was originally termed the "upper sandstone member" by Jeletzky (1967). Poulton *et al.* (1982) officially raised this member to formation status, calling it the Aklavik Formation. This was achieved at the time that Poulton *et al.* (1982) took the concept of the Bug Creek Formation (Jeletzky 1967), and extended it to include all of the Lower Jurassic to Lower Oxfordian units in the mainly arenaceous basin-margin facies, calling it the Bug Creek Group. The type section, as selected by Poulton *et al.* (1982), is located in Martin Creek, where both the basal and top contact are present. Poulton *et al.* (1982) place the base of the Aklavik Formation, for ease in mappability, at the base of the bluff forming, apparently massive sandstone that dominates the unit, distinguishing it from the less resistant, thinner bedded sandstone below. The upper contact is placed consistently where the sandstone comes in contact with the soft, black shale of the Husky Formation; this contact is sharp everywhere. Overall, these same contacts were used for the purposes of identifying the Aklavik Formation within this study.

For biostratigraphic purposes, ammonites were sufficiently abundant in the Jurassic strata and therefore useful for determining ages and correlation of many stratigraphic units in the Brooks-Mackenzie Basin (Poulton *et al.* 1982). However, due to the sparse distribution and

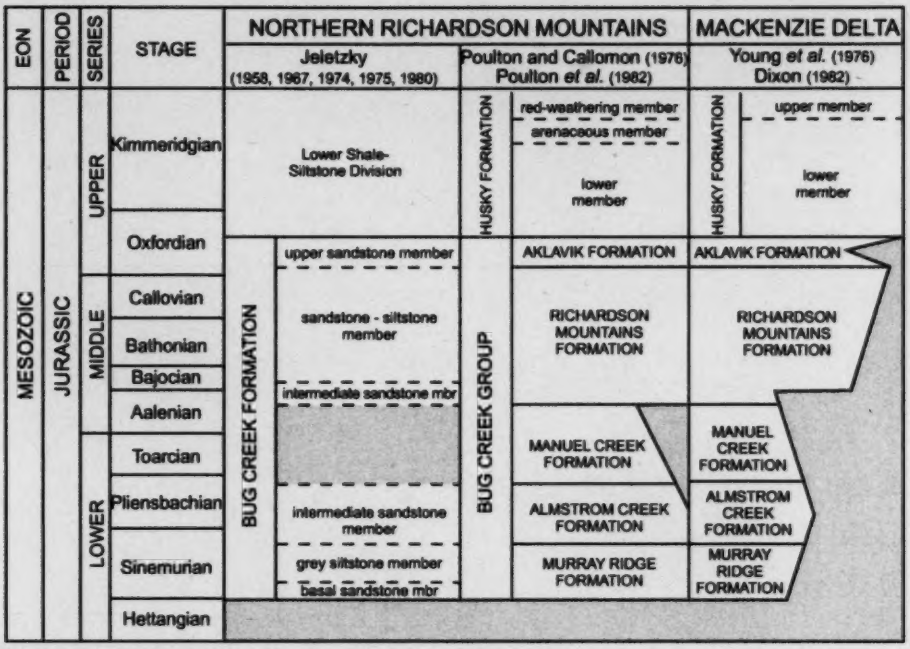


Figure 1.3 Jurassic stratigraphy in the Brooks-Mackenzie Basin. The evolution of the Jurassic strata from member to formation status is shown (modified from Dixon 1982; Poulton *et al.* 1982; Braman 1985; Poulton 1997).

commonly poorly preserved occurrences of these fossils in the northern Richardson Mountains, age determinations were based on comparisons with ammonites of northwest Europe (Arkell 1956; in Poulton *et al.* 1982) and east Greenland (Callomon 1959; in Poulton *et al.* 1982). The age of the Aklavik Formation in the area is restricted to the occurrence of fossils in the upper most beds of the Richardson Mountains Formation. The Boreal ammonite *Cardioceras* sp. was most useful for determining the age of this formation as Oxfordian (Poulton *et al.* 1982; Imlay 1984). The presence of a single, poorly preserved specimen of probable Oxfordian *Cardioceras* or *Amoeboceras* sp. in the lower part of the overlying Husky Formation restricts the Aklavik Formation to being deposited fully within the Oxfordian (Poulton 1978c). The Bug Creek Group is distinguished from the Husky Formation, biostratigraphically, by the presence of the upper Oxfordian to lower Kimmeridgian bivalve *Buchia concentrica* (Braman 1985). Where these bivalves occur in the Husky Formation, they are prolific in number. They are not known to occur in beds as old as the Bug Creek succession (Poulton *et al.* 1982).

1.7 Paleogeography and Regional Geological Setting

The Brooks-Mackenzie Basin was the depo-center for the Aklavik Formation. Balkwill *et al.* (1983) first suggested this basinal name for the depositional basin that was active between the Late Paleozoic and mid Early Cretaceous. This term was created to stress the physical continuity

and similarity of the rocks in the northern Richardson Mountains to those in northern Alaska and northern Yukon (Balkwill *et al.* 1983). Previous authors generally used the names Brooks Geosyncline when discussing strata of Alaska and Yukon, and the name Beaufort-Mackenzie Basin with regard to the Mackenzie Delta and Richardson Mountains region. It has been suggested by some authors (Tailleur 1973; Newman *et al.* 1977; Grantz *et al.* 1990) that there is evidence for a counter-clockwise rotation of Alaska away from northern Canada, commencing in the Jurassic. This continues to be a very controversial topic (see Lane 1997, 1998); it is not discussed further in this thesis, and the reader is referred to the references cited.

Figure 1.4 illustrates the regional tectonic setting of the Brooks-Mackenzie Basin during the Jurassic. The basin is bounded to the southeast and east by the North American craton, and by an apparently extensive, yet poorly documented, landmass to the north. The Brooks-Mackenzie Basin is one of two Late Paleozoic to mid Early Cretaceous depositional centers of the Arctic North America; the other is the Sverdrup Basin of the Canadian Arctic Archipelago (Balkwill *et al.* 1983). Both of these basins were separate depositional centers, but similarities in marine faunas indicate significant connections existed between the two (Balkwill *et al.* 1983). The tectono-stratigraphic phase during which these basins maintained their configuration has been called the Ellesmerian regime (Lerand 1973; Balkwill *et al.* 1983). This corresponds to a tectonic period spanning the Mississippian through to the end of the Jurassic (Lerand 1973), dominated by extensional faulting and shallow water clastic deposition, with sediments derived from the North American craton to the south and southeast (Balkwill *et al.* 1983).

Overall, throughout the Jurassic, the study area is thought to have been relatively stable geologically (Young 1973). However, the cratonic margin, commonly referred to as the Peel Landmass, is interpreted to have been unstable, resulting in erratic facies and thickness variations (Poulton *et al.* 1982). The instability of this region presumably corresponds to strike-slip faulting in the area of the Eskimo Lakes Fault Zone (see section 1.7.1), which is thought to have been active, at least periodically, during part of Jurassic deposition (Poulton *et al.* 1982; Braman 1985). Localized uplifts and depressions that were periodically active characterize this region of the Peel Landmass. Some of these tectonic elements influenced deposition and preservation of the Aklavik Formation (Poulton *et al.* 1982), and are further discussed in section 1.7.1.

As previously mentioned, the Bug Creek Group typically unconformably overlies Permian age rocks, suggesting that Jurassic deposition followed a period of Triassic uplift and erosion (Poulton 1997). Arenaceous components of this succession can be attributed to the reworking of Paleozoic sedimentary rocks. Jurassic rocks in the basin form a clastic wedge that becomes thinner, less complete, and more abundant in coarser grained material towards the southeast, in the direction of the craton and the presumed sedimentary source (Young 1973; Poulton *et al.* 1982). The overall sediment source throughout the Jurassic can be attributed predominantly as cratonic. However, these sources slowly migrated south during this time, in association with increased southward and southeastward episodic transgression of the craton by the Boreal Sea from the north (Poulton 1997). The northwest corner of the North American craton during the Jurassic was presumably made up of a shallow marine shelf that underlies the northern Richardson Mountains, northern Yukon, and

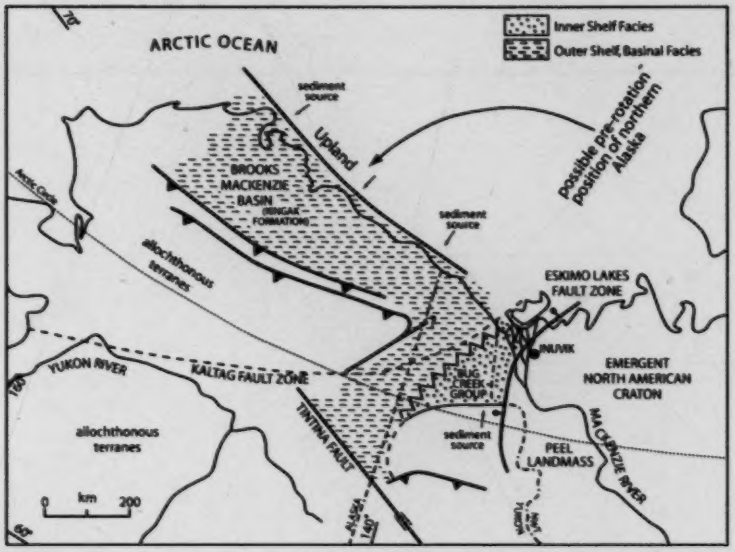


Figure 1.4 Regional tectonic setting of the Brooks-Mackenzie Basin during the Jurassic (modified from Poulton 1997).

(although perhaps tectonically dislocated) northern Alaska (Poulton 1997). The paleogeographic setting of northern North America during the Jurassic is schematically depicted in Figure 1.5.

1.7.1 Tectonic Elements

Tectonic elements that are interpreted to have influenced deposition during Jurassic time in the Brooks-Mackenzie Basin are illustrated in Figure 1.6. Numerous authors have discussed these structures, as well as others within the basin. However, only the elements deemed pertinent to the Upper Jurassic are summarized below. For a more detailed investigation into the tectonic history of the basin, the reader is referred to the references cited below.

Peel Landmass

The Peel Landmass is interpreted as the unstable, northeasterly trending cratonic margin of North America (Poulton *et al.* 1982). It is comprised of a series of uplifts and depressions that influenced sedimentation of different Mesozoic units. It is essentially an umbrella term, encompassing the other tectonic elements subsequently discussed. This structure was first recognized by Jeletzky (1961) and termed the Aklavik Arch; it has also been referred to as the Aklavik Arch Complex (Yorath and Norris 1975).

Rat Uplift

This structure was first identified by Norris (1973), and was illustrated by Jeletzky (1975) as a localized, arch-like uplift in Jurassic time, on the portion of the craton that formed much of

Figure 1.5 Schematic illustration of the paleogeographic setting of North America during the Jurassic (modified from Taylor *et al.* 1984). The study area is circled in red.

the southeast margin of deposition. Poulton *et al.* (1982) saw no evidence for it being described as a positive, typical arch feature, and interpreted it as the gentle-sloping, northwest surface of the craton. To the southeast of this feature, Poulton *et al.* (1982) predicted subaerial exposure and possible non-marine deposition and to the northwest, marine sediments of the Brooks-Mackenzie Basin.

White Mountains Uplift

The name White Mountains was first used by Norris (1973) to describe the present day dome of Paleozoic rocks. It was later recognized as an ancestral uplift by Poulton and Callomon (1976), and the term White Mountains Uplift was introduced by Poulton (1978b). This uplift was recognized when it was observed that the thick rocks of the Lower Jurassic were missing in a localized region, with the typical complete succession of strata surrounding it. Poulton *et al.* (1982) inferred that the Lower Jurassic rocks were deposited on and then subsequently eroded from the White Mountains area due to uplift during the Bajocian.

Cache Creek High

The Cache Creek High is a linear, north-south trending uplift whose primary expression was during the Late Jurassic and Cretaceous. It was responsible for separating the basin into two elements: the Blow Trough (Young *et al.* 1976) or Rapid Depression (Norris 1972) to the west, and the Kugmallit Trough (Young *et al.* 1976) or Canoe Depression (Norris 1972) to the east. This feature flanks the perimeter of the study area. Therefore it is difficult to determine, within this area, what its true affects on sedimentation were within the basin. It can be assumed that the sudden appearance of coarser grained facies relative to the surrounding area, noted by Poulton *et al.* (1982; see sections PU-19-76 and PU-20-76), as well as their interpretation of possible barrier island systems in the northwest, may have been attributed to the Cache Creek Uplift.

Tununuk High

This term was originally introduced by Lerand (1973) to describe a gravity anomaly that was less negative than the surrounding area, and interpreted as a broad, domed structure. During the Jurassic, this structure may have been responsible for the northeastern depositional margin of the Bug Creek Group.

Eskimo Lakes Fault Zone

Yorath (1973) originally used the term Kugaluk Arch to describe this assemblage of complex faults. Young *et al.* (1976) later replaced the term with Eskimo Lakes Arch. Bounding the northwest edge of this arch is the Eskimo Lakes Fault Zone (Coté *et al.* 1975; Young *et al.* 1976). This feature has

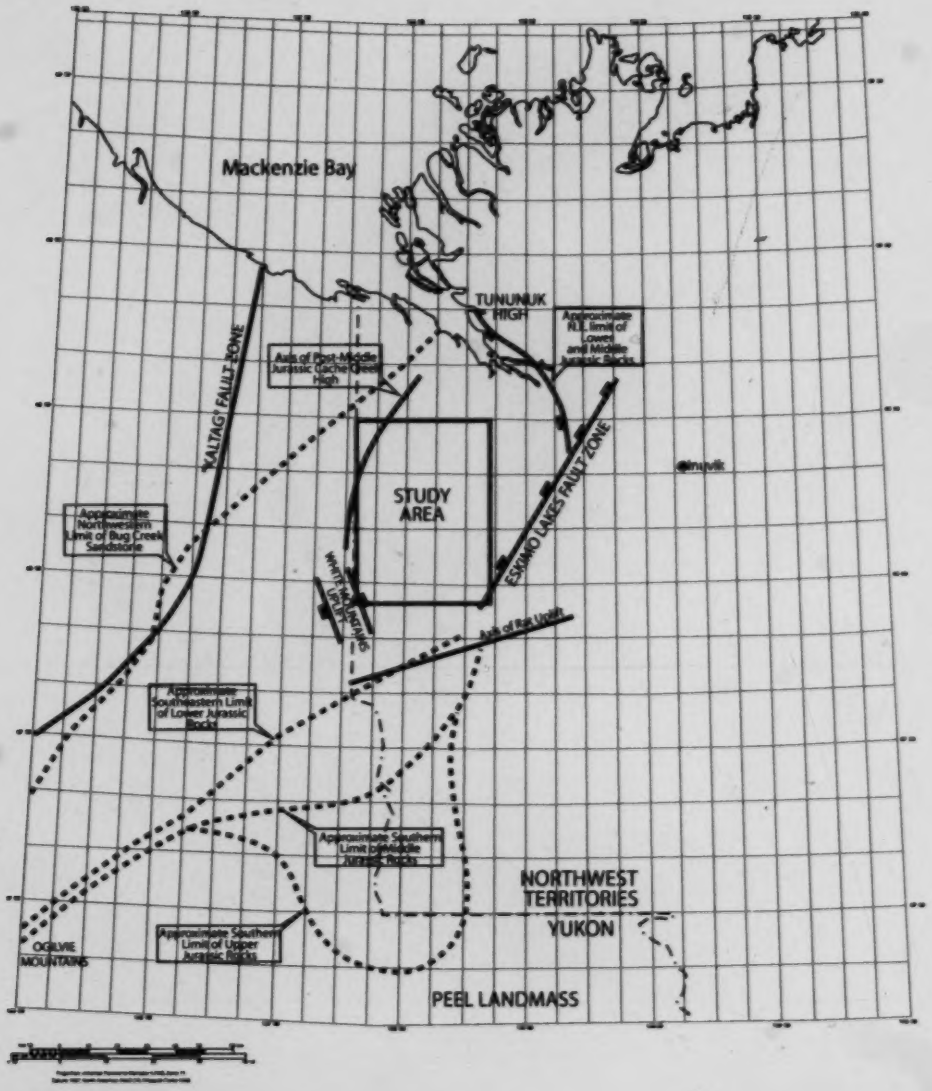


Figure 1.6 Tectonic elements that affected Jurassic deposition in the Brooks-Mackenzie Basin. Major fault zones that affected or may have affected the present distribution of Bug Creek Group rocks are also shown (modified from Poulton 1997).

also been referred to as the Tuktoyaktuk Fault Flexure Zone by Lerand (1973). It is possible that this fault zone, or a subsidiary of it, was active towards the end of the Jurassic. However, the true Eskimo Lakes Fault Zone presumably had more of an influence in the basin during Cretaceous and later time, and is therefore responsible for affecting the present day distribution of Jurassic rocks.

CHAPTER TWO: FACIES DESCRIPTIONS AND INTERPRETATIONS

2.1 Introduction

The division of the Aklavik Formation into facies was based upon defining characteristics, which include lithology, grain size, physical, and biogenic sedimentary structures. The facies in this chapter are presented in depositional order, which is also in a generalized coarsening-upward succession, aside from the last two facies. Overall, the entire package of facies that define the Aklavik Formation can be thought of as a "facies association", defined as "...groups of facies that occur together and are considered to be genetically or environmentally related" (Reading 1996). Facies associations are then useful for interpreting depositional environments from their stacking patterns. Within this study area, a single facies association is identified for the Aklavik Formation, which depicts a single coarsening upward cycle. The consideration of the facies together as a package, as well as their interaction with each other, was important for interpreting the depositional environments.

For the purpose of understanding the depositional setting of the Aklavik Formation, the overlying and underlying formations were also examined. Sections commenced generally within the upper portion of the underlying Richardson Mountains Formation, when it was adequately exposed. This allowed for a better appreciation of the nature of the contact between the two formations. Measured sections typically ended when the top of the massive sandstone of the Aklavik Formation was reached, mainly because the overlying Husky Formation was rarely present. Where the Husky Formation was observed, descriptions were noted. As a result, the facies presented within this study do not pertain only to the Aklavik Formation; portions of the underlying and overlying formations are included as well. The outcome is an enhanced interpretation of the depositional history of the Aklavik Formation.

Distinguishing characteristics of each facies, along with key interpretations, are summarized and presented in Table 2.1.

2.2 Facies Descriptions and Interpretations

Facies A: Intensely burrowed, dark brown siltstone inter-bedded with rare very fine-grained sandstone

Lithology and Sedimentary Features: Dark brown, wavy-bedded siltstone characterizes this facies (Figure 2.1 A). The color is typically brown, but frequently has reddish hues due to the presence of abundant siderite cement. Within Facies A, rare, very fine-grained sandstone beds are observed inter-bedded in the siltstone (Figure 2.1 B). These sandstone beds display very poorly developed low angle cross-laminations, which are commonly not observable due to the intensity of bioturbation; these beds are not very pervasive across the outcrop. Typically their thickness is between 10 – 25 centimeters, however their relative thickness and abundance appear to increase upwards. The lower bounding surface of these sandstone inter-beds is typically sharp, with a somewhat gradational relationship upwards into the siltstone.

Table 2.1

Summary table of all facies identified in this study, along with their distinguishing characteristics, interpreted depositional environment, and stratigraphic interval (vf = very fine; f = fine; uf= upper fine; HCS = hummocky cross-stratification; SCS = swaley cross-stratification; Ar = *Arenicolites*; Ch = *Chondrites*; Cy = *Cylindrichnus*; Di = *Diplocraterion*; He = *Helminthopsis*; Op = *Ophiomorpha*; Pa = *Palaeophycus*; Pl = *Planolites*; Po = *Polykladichnus*; Ro = *Rosselia*; Sk = *Skolithos*; Te = *Teichichnus*).

Facies	Lithology and Grain Size	Sedimentary Structures	Ichno-fossils	Interpretation	Stratigraphic Interval
A	siltstone	wavy laminae	He, Ch	deep marine, lower offshore; rare storm deposition	Richardson Mountains
B	vf grained sandstone; inter-bedded siltstone; coarsening upward trend	wavy laminae; ripples; bioclastic and organic debris	Op, Pa, Ro, Cy, Sk	upper offshore; rare storm deposition	Richardson Mountains
C	vf grained sandstone; inter-bedded mudstone	wavy laminae; ripples	Ch	fair-weather conditions of the upper offshore	Richardson Mountains
D	vf - uf grained sandstone; rare inter-bedded muddy siltstone	HCS; basal scour surfaces; ripples; organic laminae	Ro, Te, Op, Cy, Pa, Sk, Ar, Pl, Po	storm deposition in the upper offshore to lower shoreface	Aklavik; some Richardson Mountains
E	vf - f grained sandstone	SCS; scoured beds; ripples; wood lag impressions	Sk, Cy, Ar, Pa	regular storm deposition in the upper shoreface	Aklavik
F	vf - medium grained sandstone	Planar, non-erosive bedding contacts; rare ripples	Cy, Sk, Pa, Pl	deposition within the lower to upper shoreface	Aklavik
G	f - medium grained sandstone	broad, wavy bedding contacts; thick beds; frequent ripples	Pa, Pl, Cy, Sk	deposition within the lower to upper shoreface	Aklavik
H	uf - medium grained sandstone	trough cross-stratification; ripples; wood lag impressions; basal erosional surface	none observed	distributary channel fill deposits; incised into the upper shoreface	Aklavik
I	f grained sandstone	small dunes; ripples	Di	shallow water; possible tidal inlet shoals	Aklavik
J	medium - coarse grained sandstone	poorly sorted; erosional base; very thin; mud clasts and bioclastic debris	none observed	transgressive lag deposit	Aklavik
K	vf grained sandstone; silty laminae	ripples; abundant mud and organic debris	Pa, Te, Ch	fully marine, low energy, offshore	Aklavik - Husky transition
L	shale	finely bedded	none observed	shelf	Husky

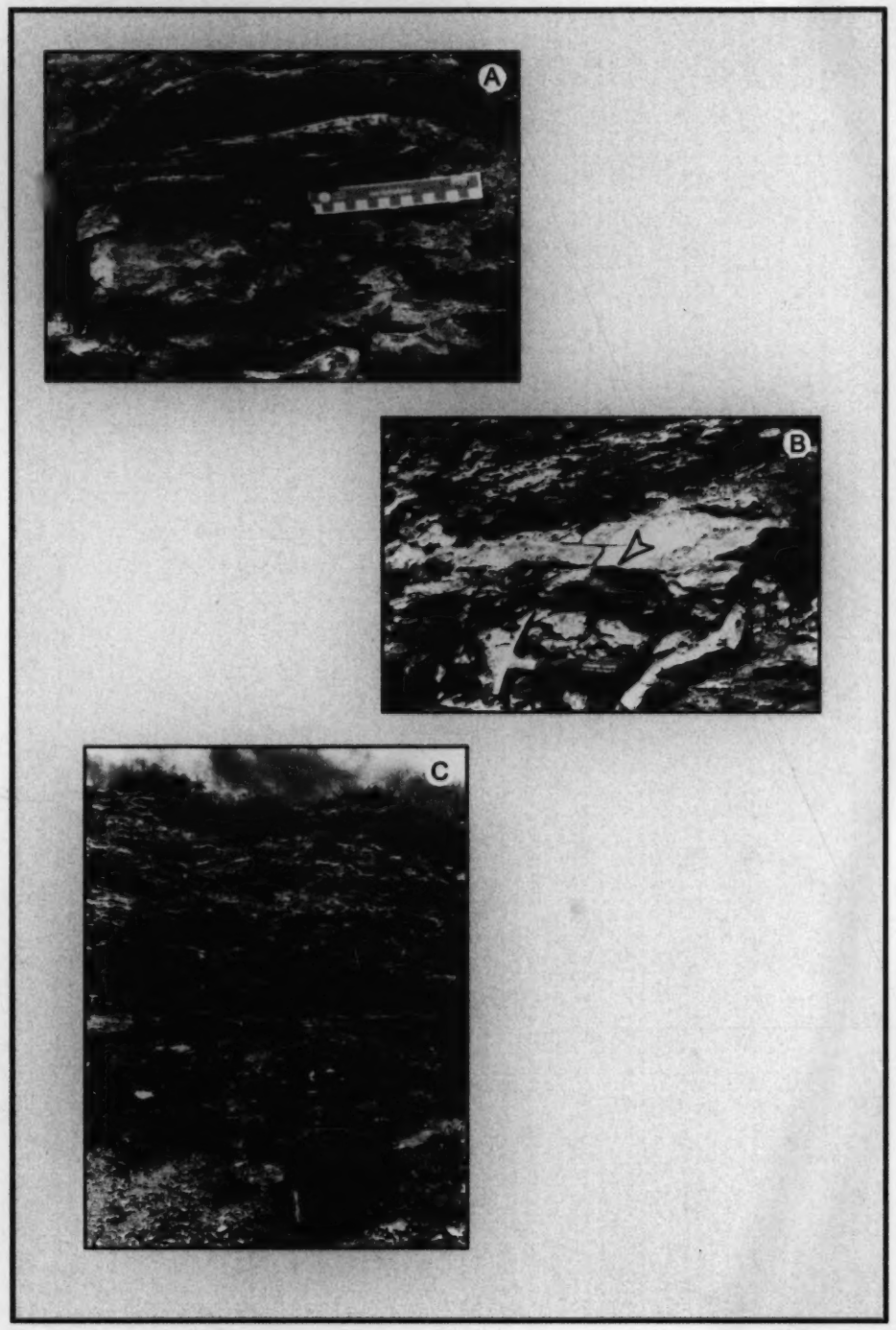
Figure 2.1

Facies A: Intensely burrowed, dark brown siltstone inter-bedded with rare fine-grained sandstone

A. Dark brown wavy bedded siltstone, with faint reddish hues due to siderite cement. Scale bar is equivalent to 15 cm.

B. Very fine-grained sandstone beds inter-bedded with siltstone. The sharp, presumably erosive basal contact of the sandstone bed is highlighted.

C. An overview of Facies A in outcrop. It is generally poorly exposed and therefore not often described in the measured sections. Note hammer for scale near bottom of photo.


A
B
C

This facies is rarely described in outcrop, as it is generally recessive and not readily exposed (Figure 2.1 C). Where visible, Facies A is commonly found in poorly preserved slabs.

Ichnology: Bioturbation is limited to the finer grained portion of Facies A, where intense bioturbation can be observed. In these horizons, traces are dominated by the ichnogenera *Helminthopsis* and *Chondrites*. The sandstone beds do not lack bioturbation, but relative to the siltstone beds, are not as fully reworked.

Interpretation and Discussion: Facies A is identified as being part of the Richardson Mountains Formation. Based on the grain size, wavy laminations, bioturbation levels, and types of traces identified, Facies A is interpreted to represent deposition within relatively low energy, deeper marine conditions of the lower offshore. The dominant sedimentary structures are wavy laminasets. These structures are interpreted as fair-weather deposits, associated with the lower offshore. Organisms had plenty of time to rework the sediment, hence the high degree of bioturbation observed in the facies. The trace fossil assemblage is classified as part of the distal *Cruziana* ichnofacies (Sielacher 1967), which is indicative of the lower offshore (Frey *et al.* 1990; Pemberton *et al.* 1992).

One of the most useful tools resulting from ichnology involves the grouping of characteristic ichnofossils into recurring ichnofacies. This concept was originally identified by Seilacher (1967), and modified into the modern ichnofacies concept by Frey *et al.* (1990). This concept is commonly used, and is valuable in environmental reconstruction. Characteristics of the *Cruziana* ichnofacies are summarized in Table 2.2.

Facies A contains isolated sandstone beds, characterized by poorly developed cross-bedding and moderate bioturbation. The lack of bioturbation associated with these beds suggests rapid sedimentation rates. These beds reflect a change from the typical conditions associated with Facies A. The sand was introduced to the lower offshore setting by rare storm events. Due to the isolated nature of the storm beds, they are not considered a separate facies, but are more appropriately grouped with Facies A. Facies A reflects deposition under fair-weather conditions, well below fair-weather wave base, and possibly very near to storm weather wave base, with the periodic influx of storm deposits. A detailed discussion on the divisions of a shoreface is included in Chapter 3, section 3.3.

Baird *et al.* (1986) suggested that the presence of siderite indicates three key conditions: a) availability of iron, b) rapid burial of organic material, c) and a low to non-existent supply of sea water sulfate, allowing for methanogenic reactions. These three conditions are commonly found within fresh to brackish water environments, where siderite formation is most predominant (Baird *et al.* 1986). Within the marine realm, the conditions under which siderite is stable are severely restricted (Berner 1971; Maynard 1983). The necessary conditions include a low Eh, which can be produced from the anaerobic bacterial decomposition of organic matter (Berner 1971). However, Berner (1971) stated that in marine settings, the typical outcome was sulfate reduction due to the abundance of dissolved sulfate. Siderite therefore only forms in marine settings where sulfate reduction is inhibited; this situation is unusual, and therefore the formation of marine siderite cement is rare (Berner 1971). This harsh water chemistry would have created conditions that were

Table 2.2

Summary table of the three ichnofacies, as defined by Frey *et al.* (1990), identified in the study area of the Aklavik Formation (modified from Pemberton *et al.* 2002).

Ichnofacies	Characteristics	Interpretation
Cruziana	- mixed association of vertical, inclined, and horizontal structures - structures made by mobile organisms - generally high diversity and density - mostly feeding and grazing structures constructed by deposit feeders	- characteristic of subtidal, poorly sorted, unconsolidated substrates - generally moderate energy levels in shallow waters, below fair-weather wave base - also found in low energy levels in deeper water
Skolithos	- predominantly vertical, cylindrical, or U-shaped burrows - few horizontal structures - dwelling burrows constructed by suspension feeders - low diversity, but individual forms may be abundant	- relatively high levels of wave or current energy - typically developed in clean, well-sorted, loose or shifting substrates - commonly occurs in foreshore and shoreface of beaches, but not indicative of these environments alone
Glossifungites	- substrate controlled assemblage; defined as a firm ground ichnofacies - vertical, cylindrical, tear- or U-shaped dwelling burrows - constructed by suspension feeders or animals that leave their burrow to feed - low diversity, but individual forms may be abundant	- forms in a wide range of environments, but limited to firm, unlithified substrates - demarcates erosional discontinuities associated with a depositional hiatus

not suitable for all organisms. This feature is reflected in the preservation of an impoverished trace fossil assemblage in Facies A. Typically, a diverse suite of trace fossils characterizes the offshore setting (MacEachern and Pemberton 1992), but the conditions during deposition of Facies A were too extreme to allow for a typical benthic community to flourish. For a more in depth discussion on siderite formation and required conditions, the reader is referred to Berner (1971) and Maynard (1983).

The *Cruziana* ichnofacies is characterized by a diverse group of trace fossils. However, Facies A has very limited identifiable traces. This could be for three reasons: a) this facies is highly recessive, and therefore the full suite of trace fossils was not observed due to poor preservation; b) bioturbation levels were so intense that, due to extreme reworking of the sediment, only *Chondrites* and *Helminthopsis* could be identified; or c) the conditions at the time of bioturbation were not conducive for a diverse assemblage of organisms to exist, and therefore only highly adaptive forms were able to survive and successfully exploit the sediment (Pemberton and Frey 1984; Pemberton *et al*. 2002). The preservation of sedimentary structures, the presence of siderite cement, and the relatively low diversity of trace fossils, including *Chondrites*, a species interpreted as indicating low oxygen (see Facies C Interpretations for a detailed discussion on this topic), suggests that the depositional environment experienced ecological stresses that were not conducive for the general burrowing fauna. The combination of all three factors strongly suggests that the harsh marine water chemistry, particularly the reduced oxygen within the system, was the primary limiting agent reducing bioturbation

Facies B: Very fine-grained sandstone with abundant inter-bedded siltstone

Lithology and Sedimentary Features: Facies B is dominantly comprised of fine-grained sandstone with abundant inter-beds of siltstone. Wavy laminae, or bedding, is the dominant sedimentary feature associated with the sandstone beds; ripple laminae are also common. Organic laminae are present (Figure 2.2 A), as well as bioclastic debris. Overall, this facies exhibits a cleaning or coarsening upward trend, due to the inter-bedded siltstone becoming less frequent.

The thickness of this facies ranges between 30 centimeters to nearly 2 meters. Facies B is poorly exposed, due to its recessive nature. Where exposed, it is made up of highly broken, flaggy pieces of rock (Figure 2.2 B). This facies is similar in description to Facies K, but it is not included with it due to the thickness variation of Facies B, as well as its stratigraphic position within an outcrop. Facies B gradationally overlies Facies A; essentially the main difference between these two facies is that Facies B has a higher content of sand relative to finer grained material. In some localities, thin beds of Facies D can be observed inter-bedded locally (Figure 2.2 B, C).

Ichnology: The ichnogenera identified in Facies B include horizontal *Ophiomorpha, Palaeophycus, Rosselia, Cylindrichnus,* and rare *Skolithos* (Figure 2.2 A) . The intensity of bioturbation ranges between rare and intense, but is commonly moderately burrowed.

Interpretation and Discussion: Based on its stratigraphic position and recessive nature, Facies B, like Facies A, is also considered part of the Richardson Mountains Formation. The sedimentary structures and dominant grain size of this facies indicate deposition within an overall low energy

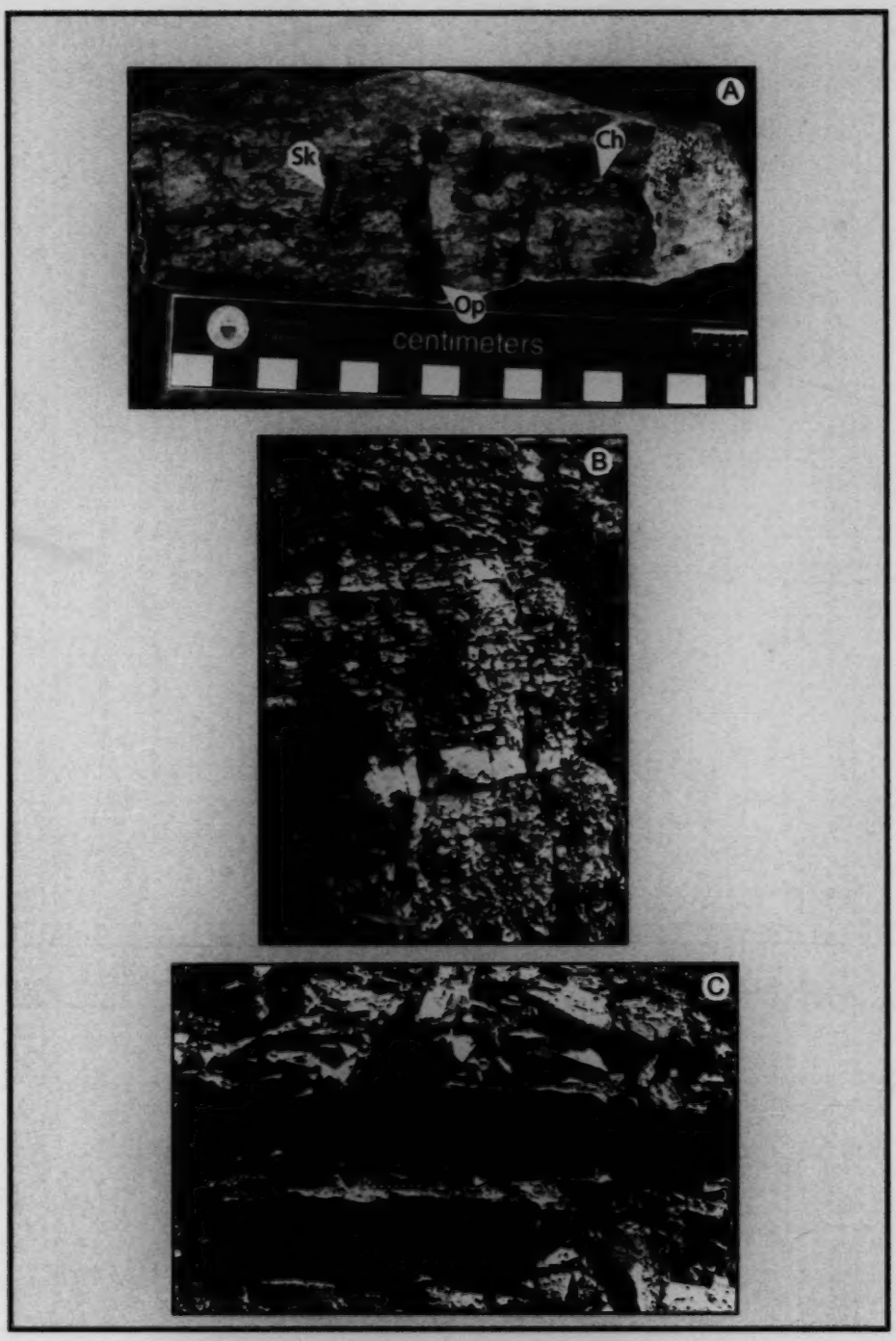
Figure 2.2

Facies B: Very fine-grained sandstone with abundant inter-bedded siltstone

A. Slabs of very fine-grained sandstone with common muddy organic laminations. *Skolithos* (Sk), *Ophiomorpha* (Op), and *Chondrites* (Ch) are typical traces.

B. Typical appearance of outcrop of Facies B. Facies D can be observed inter-bedded within Facies B. A thin bed of Facies D is present, the basal surface in contact with the end of the hammer handle.

C. Facies B is typically exposed as broken, flaggy pieces of rock. A possible broken up bed of Facies D is pictured here. Note scale in center of photo.


A
Sk
Ch
Op
centimeters
B
C

setting, interpreted as the upper offshore. Relative to Facies A, depositional conditions were somewhat more energetic; this is supported by the occurrence of sub-vertical to vertical trace fossils, as well as by the increased grain size. The close association of Facies B with intermittent beds of Facies D (interpreted as storm beds, as outlined in Facies D Interpretations) also supports an increase in energy level. This increase corresponds to a slight decrease in water depth, relative to Facies A. As a result, storms were able to penetrate the substrate of Facies B on a more regular basis, relative to Facies A. This association also supports deposition below fair-weather wave base, but within storm wave base, corresponding to the upper offshore (MacEachern and Pemberton 1992; Pemberton and MacEachern 1995).

The abundant ripples are interpreted to be oscillation ripples, possibly associated with waning storm currents. These structures formed from regular wave motion along the ocean floor, where the velocity of the flow in one direction was greater than the velocity in the opposed direction (Harms *et al.* 1975).

Organic and bioclastic debris were supplied to the facies by initial storm currents, which were strong enough to affect the upper offshore. However, storms were only powerful enough to result in irregular disturbances of this setting, therefore allowing these beds to be periodically preserved, rather than eroded by ensuing storms. The decrease in siltstone upwards in the facies also reflects the influence of storms, resulting in more sand being transported into the system via storm currents.

Within the idealized shoreface model of Pemberton and MacEachern (1995), based upon Cretaceous data from the Western Canadian Sedimentary Basin, the proximal *Cruziana* ichnofacies is typically associated with deposits above fair-weather wave base, specifically the lower shoreface (Figure 2.3). This differs for the Aklavik Formation, where Facies B, characterized by a proximal *Cruziana* assemblage, is interpreted as upper offshore deposits, and therefore below fair-weather wave base. This relationship is the result of the Aklavik Formation being deposited within a depocenter that was easily accessible to the open ocean. Consequently, the overall water energy was much greater, when compared to that of the shallow seaway of the Western Canadian Sedimentary Basin at the time of the Cretaceous (Williams and Stelck 1975), and the resident benthic community adapted to the increase in water energy by abandoning deposit feeding behaviours for more efficient, suspension feeding mechanisms. Also, as the facies indicate, the Aklavik Formation was deposited during a time of persistent large storms.

Facies C: Very fine-grained sandstone with inter-bedded, *Chondrites*-rich mudstone

Lithology and Sedimentary Features: Facies C is comprised of very fine-grained sandstone with inter-bedded mudstone that is not locally extensive (Figure 2.4 A). The sand to mud ratio is roughly 3:1, but can be locally variable. The bedding thickness ranges between 5 to 20 centimeters, but rarely are thicknesses of 20 centimeters reached. Wavy-bedded, laminated sandstones characterize this facies (Figure 2.4 B), and well-developed, rounded ripples are also visible (Figure 2.4 C). Moderate amounts of siderite cement are present in some sections.

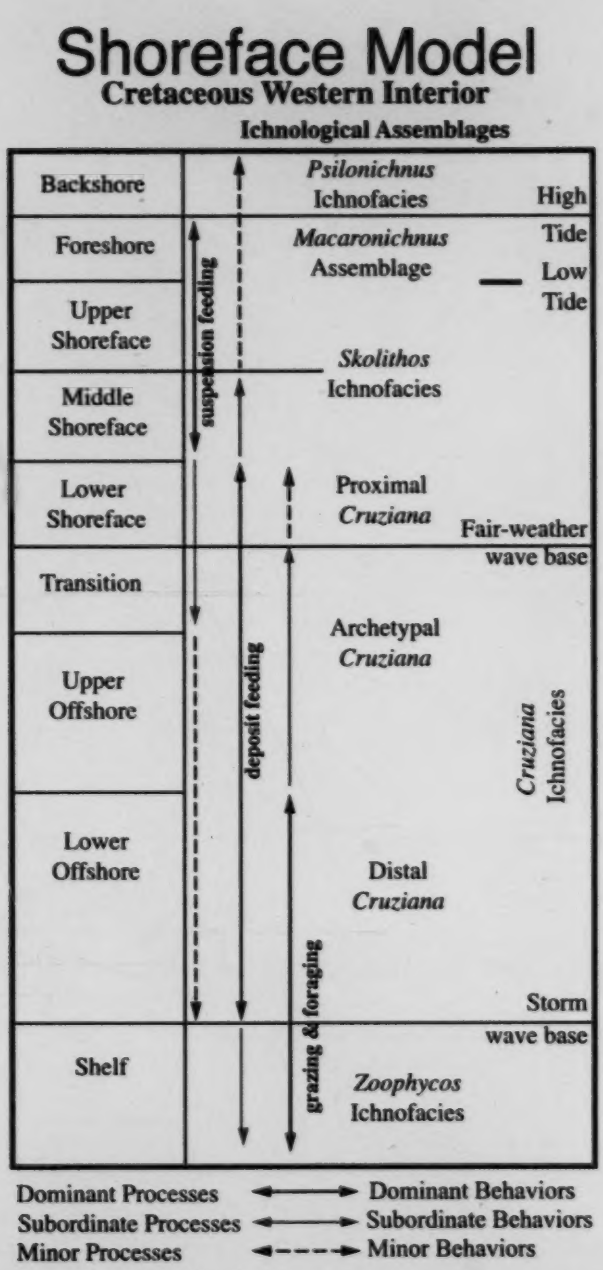


Figure 2.3 Idealized shoreface model used in this study. This model, by Pemberton and MacEachern (1995), is based on data from Cretaceous strata of the Western Interior Seaway of North America. The divisions of the shoreface are identified, along with the corresponding typical ichnofacies (modified from Pemberton and MacEachern 1995).

Figure 2.4

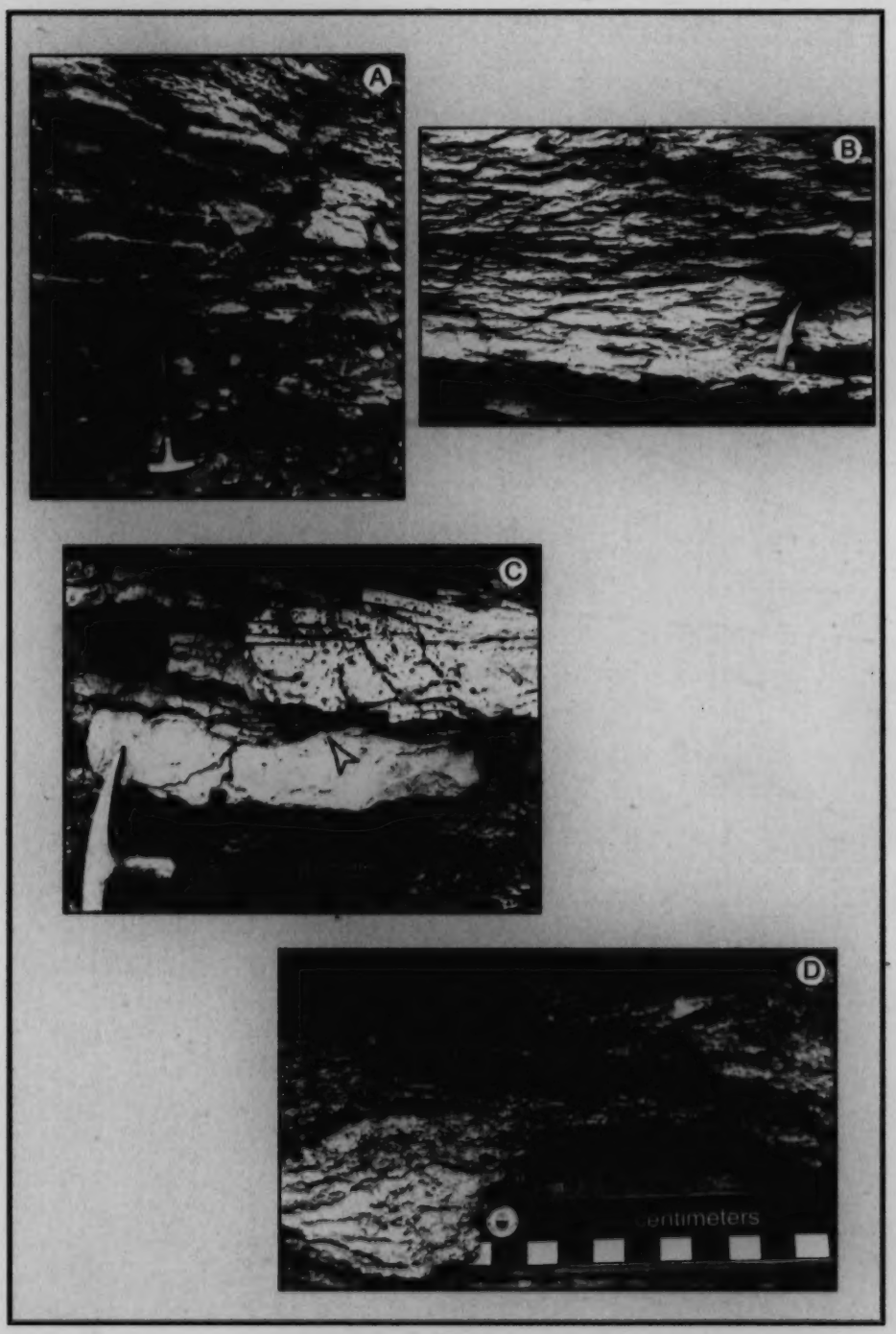
Facies C: Very fine-grained sandstone with inter-bedded, *Chondrites*-rich mudstone

A. Very fine-grained sandstone with thin inter-beds of mudstone make up Facies A. The mudstone is typically not laterally extensive across the outcrop.

B. The most dominant and observable sedimentary structures are wavy laminations, typical of the sandstone.

C. Well-rounded ripples are observed, as highlighted in this photo.

D. The mudstone beds display a monospecific assemblage of *Chondrites*, interpreted to be indicative of limited oxygen supply to the system.


A
B
C
D
centimeters

This facies is not widespread throughout the study area, and is present only locally. Where observed, it reaches a maximum thickness of four meters. It can sometimes be seen as repetitive cycles of inter-beds with Facies D.

Ichnology: Bioturbation in Facies C is restricted mostly to the finer-grained beds, where the intensity of burrowing ranges from moderate to intense. The intensely bioturbated beds typically display a monospecific assemblage of *Chondrites*, which is the defining feature of this facies (Figure 2.4 D). Other trace fossils are preserved tracks and trails along bedding planes.

Interpretation and Discussion: This facies is similar to Facies B in that it represents deposition predominantly under fair-weather conditions, above storm wave base but below fair-weather wave base. The dominance of wavy laminated bedding supports deposition under these conditions. The inter-bedded mudstone suggests that at times, Facies C experienced periods of very slow sedimentation, purely from suspension fall-out. The infrequent occurrence of inter-bedded Facies C and D (interpreted as storm beds; see Facies D Interpretations) suggests that a relationship exists between Facies C and storm deposition. Facies C is interpreted to represent deposition within the upper offshore.

The monospecific assemblage of *Chondrites*, which characterizes Facies C, is an important indicator of paleo-ecological conditions. The trace fossil *Chondrites* was created by a relatively deep burrowing organism, searching for buried organic material (Bromley and Ekdale 1984). Bromley and Ekdale (1984) predicted the superabundance of *Chondrites* in conditions where an anaerobic organic rich layer exists below the redox boundary. In this situation, the organism maintains communication with oxygen-rich waters at the seafloor, but is able to burrow into anoxic sediments for the purpose of exploiting nutrient rich layers. Accumulation of decaying material results in anoxic conditions below the sediment-water interface (Baird *et al.* 1986). This situation can result from post-storm mud deposits where the mud was buried before recolonization by bioturbating organisms had taken place (Vossler and Pemberton 1988). This scenario could easily occur in a setting that experienced periodic pulses of sedimentation due to storms. The association of Facies C with inter-beds of Facies D supports this idea in the Aklavik Formation. The result would be nutrient rich sediment accumulation below the reach of most organisms (Vossler and Pemberton 1988). The exclusion of other trace fossils within these mudstone layers and the dominance by *Chondrites* suggest that oxygen was the limiting factor for the benthic community, and was controlling the trace fossil distribution. The *Chondrites* trace maker, characterized as opportunistic (see Chapter 3, section 3.4.1), took advantage of an unexplored niche that more general species were not able adapt to.

Facies D: Unburrowed to moderately burrowed undulating fine-grained sandstone, with rare muddy siltstone inter-beds

Lithology and Sedimentary Features: This facies is composed dominantly of well sorted, very fine-grained to upper fine-grained sandstone, with rare inter-beds of muddy siltstone (Figure 2.5 A). Individual bed thickness is usually 1 meter, but ranges between 0.8 and 1.5 meters. A low amplitude undulation is characteristic of these beds, with wavelengths in excess of 1 meter (Figure 2.5 A - C). Each bed distinguishing this facies displays a gentle curvature, both concave-upward

Figure 2.5

Facies D: Unburrowed to moderately burrowed undulating fine-grained sandstone, wtih rare muddy siltstone inter-beds

A. Fine-grained sandstone with rarely preserved inter-beds of siltstone comprise Facies D. Note the hammer for scale, which sits along the scoured basal surface of one of the beds.

B. The undulating beds of Facies D are interpreted as HCS. The dips of individual beds in this photo are exaggerated; typically the beds show broad, very low-angle undulations.

C. Typical pinching and swelling of the HCS beds; pinching due to scouring from the overlying HCS bed.

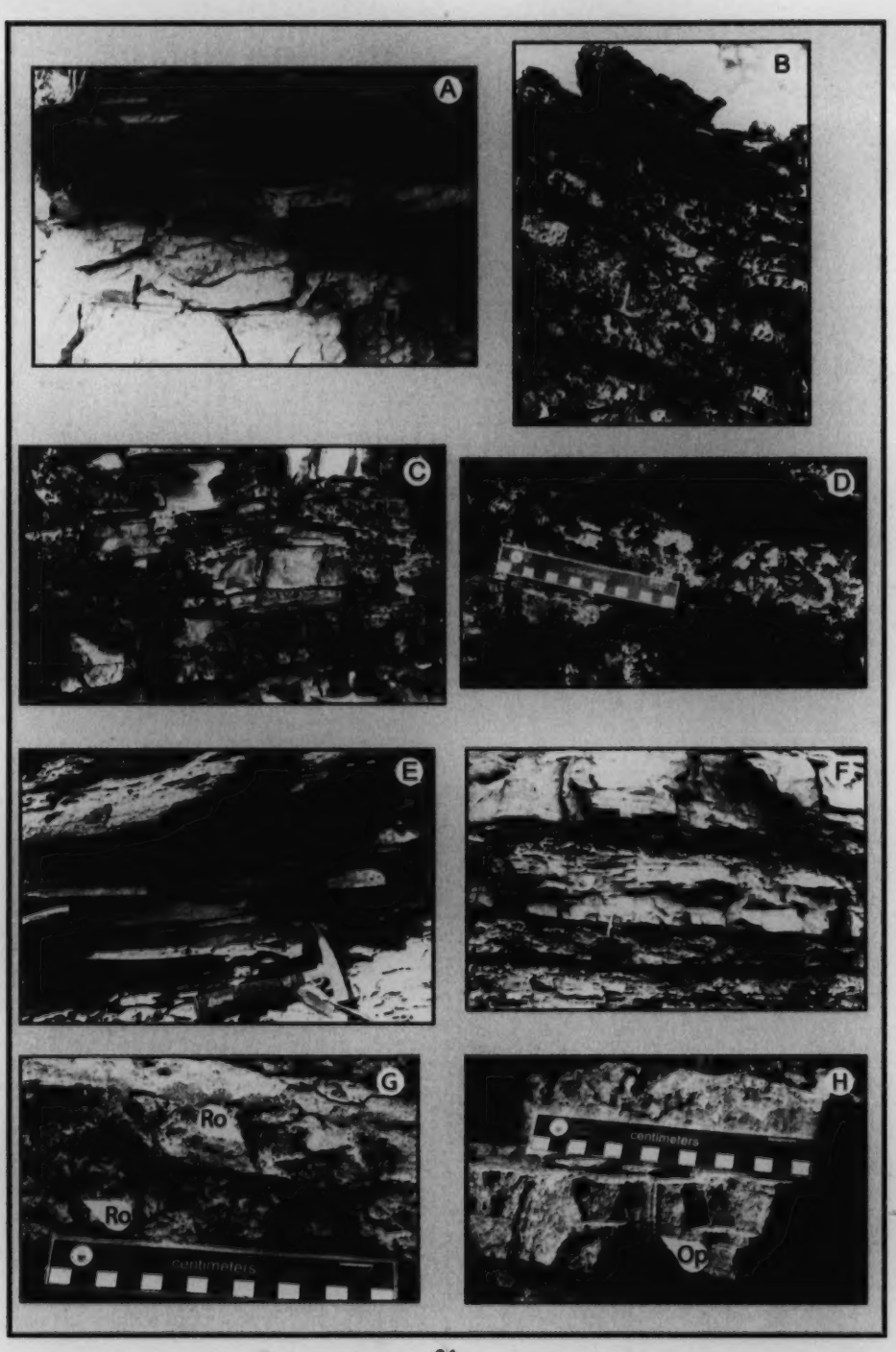
D. Symmetrical to somewhat asymmetrical ripples mantle the sandstone beds.

E. Two main styles of HCS can be observed in outcrop. The most common type, shown here, is made up of amalgamated sandstone beds, with the inter-bedded siltstone missing due to storm scouring. This style is also shown in B and C.

F. Muddy siltstone is rarely preserved between sandstone beds. Where it is preserved, it is typically well-bioturbated, giving it a mottled appearance relative to the sandstone.

G. *Rosselia* (Ro) traces, with their typical bulbous heads missing due to erosion from subsequent storms.

H. Vertical *Ophiomorpha* (Op); its presence, rather than horizontal forms, suggests water energy was relatively high during deposition.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and concave-downward. The internal stratification can only be observed in well-exposed localities, which are rare. Scour surfaces are also very common along the basal bedding contacts (Figure 2.5 A). The beds are commonly mantled by small-scale ripple laminations that appear to be symmetrical to somewhat asymmetrical in profile (Figure 2.5 D). The sediment contains organic debris (rare to common, but no more than 15%), sometimes as thin laminations. This fine-grained organic material appears to be preserved platy plant matter, and tends to be more concentrated towards the tops of beds.

There is some variation in bedding style; most commonly, the sandstone beds appear to be amalgamated, with the muddy siltstone beds absent (Figure 2.5 E). In localized regions, the thin (roughly 5 to 30 centimeter) muddy siltstone beds are preserved, and sit directly on top of the thick sandstone beds (Figure 2.5 F). Moving upward in any given section, the general trend within Facies D appears to be a decrease in the amount of mud corresponding to an increase in the amount of fine sand. The overall thickness of this facies varies between 1 and 11 meters, but is generally measured at 3 meters. Facies D is best preserved in the eastern part of the study area, where both the amalgamated sandstone beds and the rarely preserved beds of muddy siltstone can be observed (Figure 2.5 F).

Ichnology: The density of bioturbation is variable from outcrop to outcrop, as well as laterally within a single stratum. The intensity ranges from absent to moderate, with a low intensity being most typical. Moderately bioturbated zones are characterized by an assemblage comprised of the following nine ichnogenera: *Cylindrichnus*, *Rosselia*, *Teichichnus*, *Ophiomorpha*, *Arenicolites*, *Palaeophycus*, *Planolites*, *Skolithos* and rare *Polykladichnus* (Figure 2.5 G, H; Figure 2.6). This assemblage typically affects the inter-bedded muddy siltstone or the uppermost tops of the sandstone beds. When present, this assemblage appears to be comprised of relatively robust traces. Locally, sandstone beds with exceptionally high occurrences of *Rosselia* can be observed (Figure 2.5 G).

Interpretation and Discussion: The defining feature of Facies D is the curvature of the beds, which display a well-developed concave-upward and concave-downward undulation. This undulation is interpreted as hummocky cross-stratification (HCS), which is now commonly accepted to be indicative of storm deposition. Harms *et al.* (1975) formally introduced the term "hummocky cross-stratification", after Campbell (1966) originally identified these bedforms as large-scale truncated wave ripple laminae. Scoured basal surfaces, associated symmetrical ripples, laterally persistent beds, and low angle laminations, where visible, were also distinguishing features of this facies that were useful for the interpretation.

Controversy surrounds the interpreted origin of HCS, and the associated hydrodynamics. The formation of HCS has been thought to be similar to that of wave formed ripples, but with a stronger wave action with surges of greater displacement and velocity than those required to form ripples (Harms *et al.* 1982). Harms *et al.* (1975, 1982) and Dott and Bourgeois (1982) favour this purely oscillatory flow model, where hummocks and swales are reworked by elevated wave orbitals. The evidence used for this interpretation includes the association with wave ripples, the lack of obvious directional trends, the mantling relationships of laminae to lower set boundaries, and the sharp

Figure 2.6

Facies D (continued)

A. The tops of sandstone beds show few traces; *Arenicolites* (Ar) and *Skolithos* (Sk) shown here.

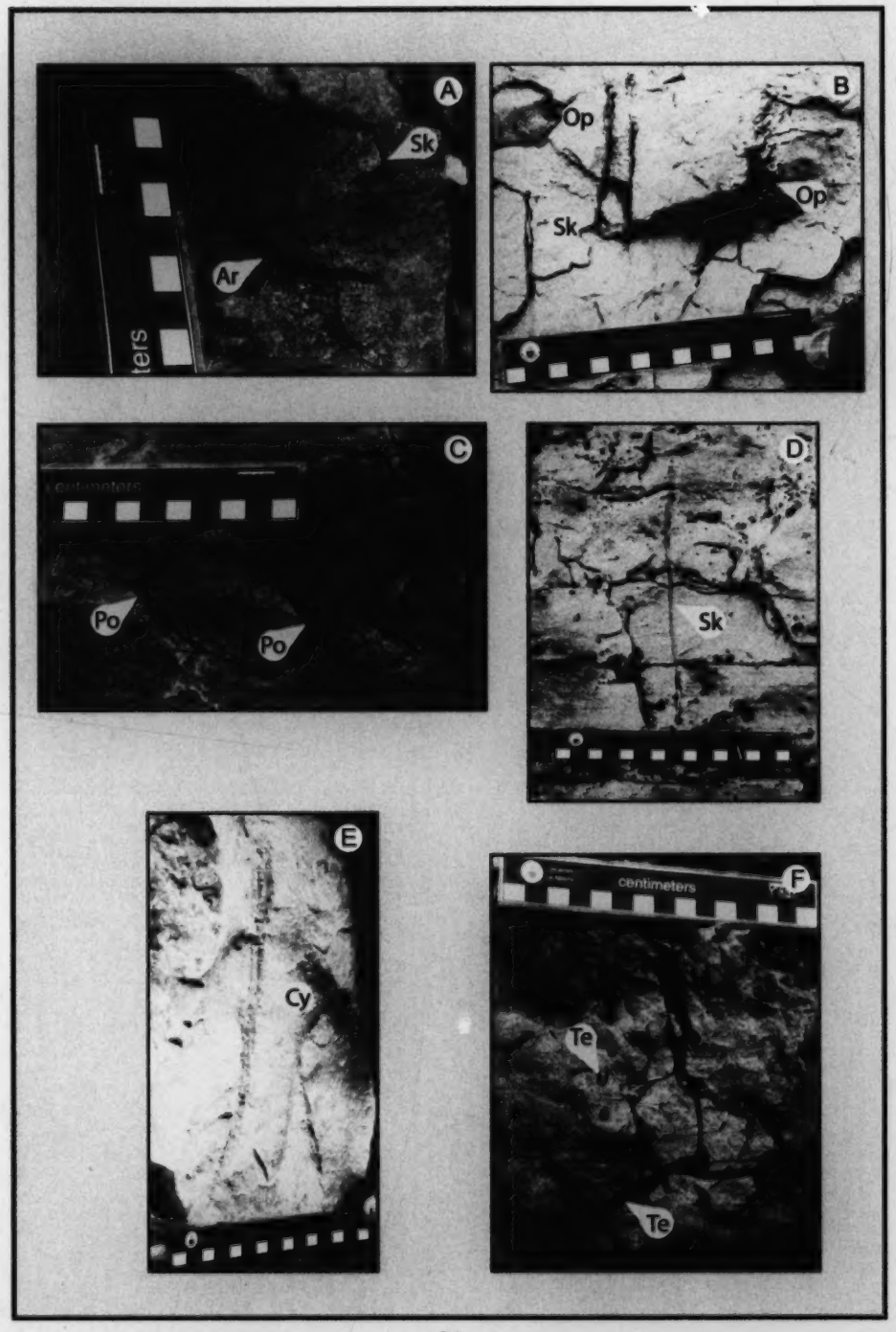
B. *Skolithos* (Sk) and *Ophiomorpha* (Op).

C. *Polykladichnus* (Po).

D. *Skolithos* (Sk)

E. *Cylindrichnus* (Cy)

F. *Teichichnus* (Te); most traces observed in separate, distinct assemblages, rather than appearing inter-mixed together.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basal contacts with some drag marks (Harms *et al.* 1975; 1982). More recent experimental flume studies in fine-grained sand support this hypothesis (Southard *et al.* 1990).

Numerous authors (Swift *et al.* 1983; Allen 1985; Nottvedt and Kreisa 1987) have suggested that HCS forms under combined oscillatory and unidirectional currents. Hunter and Clifton (1982), Leckie and Krystinik (1989), and Duke *et al.* (1991) agreed with this, but emphasized that the influence is very strongly an oscillatory dominant flow, with only a weak, shore-normal, combined flow component. Along most modern day coasts, intense wave activity is accompanied by geostrophic currents, which typically flow shore-parallel or shore-oblique due to the Coriolis Effect (Davis 1977; Leckie and Krystinik 1989). Considering this modern interaction of different oceanic currents, it is highly likely that HCS in the rock record would have formed in response to a combined flow regime between oscillatory and unidirectional currents (Swift *et al.* 1983; Swift and Nummedal 1987). However, it is important to emphasize that there is no conclusive evidence to indicate that HCS formed as a result of currents flowing parallel to the shoreline; most paleocurrent data collected from these types of deposits (Leckie and Krystinik 1989) suggests otherwise, supporting a combined oscillatory-dominant flow with a weaker, shore-normal combined flow component. Therefore, it cannot be assumed that geostrophic currents, as they are understood today, played a role in the deposition of HCS or other storm related deposits (Leckie and Krystinik 1989).

Whatever the specifics may be in the formation of hummocky cross-stratification, most workers agree that HCS is attributed to the action of storm waves (Harms *et al.* 1975; Dott and Bourgeois 1982; Swift *et al.* 1983; Duke 1985), which affect the sediment typically below the fair-weather wave base. Hummocky cross-stratification within Facies D is interpreted as storm deposition within the upper offshore to lower shoreface. A genetic link has been demonstrated between HCS and large storms, such as hurricanes and intense winter storms (Duke 1985). This topic is discussed in greater detail in Chapter 3, section 3.2.3.

Figure 2.7 depicts an idealized sequence for HCS, summarized by Dott and Bourgeois (1982). The sequence is initiated with an erosional surface that may or may not show sole marks or a lag. The overlying characteristic hummocky zone represents peak storm energy and reworking of the sediment. This grades upward into wave ripple laminae, indicative of the waning stages of the storm surge. This lower portion is then overlain by a typically bioturbated mudstone or shale, indicative of possible fair-weather conditions or the final waning stages of the storm. Variations from this idealized sequence result from a change in any of the following factors: relative sand supply, water depth, tidal range, frequency, duration and intensity of storms, and relative productivity of a burrowing benthos (Dott and Bourgeois 1982).

Two main types of HCS, as defined by Duke (1985) were identified: (1) inter-bedded lithologies, where HCS sandstone beds are inter-bedded with bioturbated muddy-siltstone; and (2) amalgamated sandstones, which consist of many HCS sandstone beds, all in erosional contact. The second type of HCS is the most common type observed in this study area. This is variable from the idealized HCS sequence of Dott and Bourgeois (1982), which includes a typically thin, highly bioturbated mudstone layer at the top. Preserved along the top of many sandstone beds are well-rounded ripples; they are oscillation to combined flow ripples, formed during the reworking of the tops

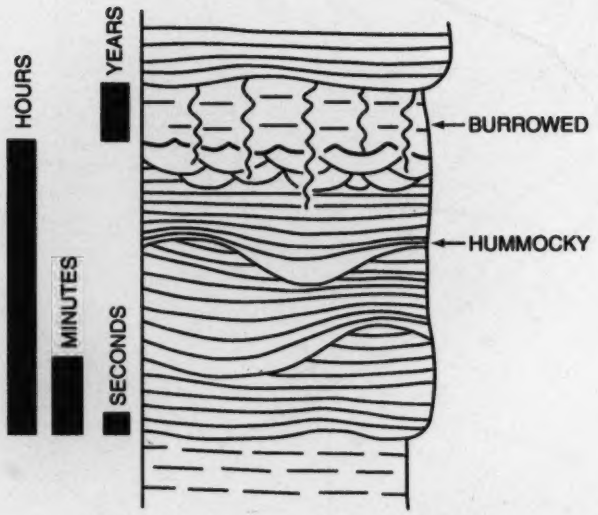


Figure 2.7 Schematic sequence of a single HCS interval, displaying the temporal significance of the different components (modified from Dott and Bourgeois 1982; Dott 1983).

of the storm beds by the waning effects of storms or by fair-weather wave processes (Dott and Bourgeois 1982; Duke 1985).

Within this facies, the general upward trend noted is one of an increase in fine sand and amalgamation of the hummocky beds, which corresponds to the eventual lack of muddy siltstone. This general trend reflects a combination of enhanced depth of scouring, due to shoaling water depth, and storm frequency (MacEachern and Pemberton 1992). Where the mudstone layer of the idealized sequence is preserved, it is generally only associated with storm deposits near the base of measured sections. The presence and stratigraphic position of this type of HCS, where thin fair-weather deposits are included, is interpreted to represent bathymetrically deeper settings, such as the upper offshore, where only large storm surges were able to rework the sediment (Dott and Bourgeois 1982).

Studied examples of HCS rarely show evidence for reworking by fair-weather conditions, such as unidirectional tidal or rip currents (Dott and Bourgeois 1982; Walker 1982). The lack of reworking is commonly used as evidence for HCS being deposited above storm wave base but below fair-weather wave base (Walker 1982). In relation to the Aklavik Formation, preserved beds of amalgamated HCS are interpreted to have been deposited above fair-weather wave base. Their lack of reworking reflects the frequency of storms, therefore preventing any major fair-weather conditions from destroying the HCS beds. The depth of formation of this bedform is also disputable; Harms (1979) estimated HCS formed in water depths ranging from 5 to 30 meters, where as Hunter and Clifton (1982) indicated a depth as shallow as 2 meters was possible for HCS formation. In the study area, HCS was deposited both below and above fair-weather wave base. The more typical HCS, displaying inter-bedded lithologies, characterizes deposits of the upper

offshore to transition zone, therefore being deposited below fair-weather wave base. Amalgamated HCS beds characterize the lower shoreface of the Aklavik Formation, implying deposition above fair-weather wave base.

Facies D spans two formations in the study area. In the upper part of the Richardson Mountains Formation, it is preserved as isolated sandstone storm beds within an overall siltstone setting. These isolated hummocks were probably deposited very close to the storm wave base boundary, where the majority of deposition resulted from fair-weather conditions. Only the strongest of storm waves would have been able to episodically interrupt this environment. Typically, Facies D gradationally overlies Facies B, with the increased occurrence of inter-beds of Facies D visible moving up section. The upper boundary of Facies D is gradational with Facies E, and is commonly very subtle.

A relatively low density of bioturbation typifies the ichnological character of Facies D, which is not uncharacteristic of storm deposits (MacEachern and Pemberton 1992). Overall, the ichnofossils appear to be somewhat of a mixed *Skolithos-Cruziana* assemblage (see Table 2.2). Traces such as *Skolithos* and *Arenicolites*, identified as part of the *Skolithos* ichnofacies, represent opportunistic species that have taken advantage of uncolonized substrates, which have developed following storm surges. Traces characteristic of the *Cruziana* ichnofacies, which include *Rosselia* and *Teichichnus*, are more commonly associated with the fair-weather deposits capping some HCS cycles. These traces represent the resident community of benthic organisms that were frequently scoured away by storm currents. The concepts of opportunistic and equilibrium species are discussed in detail in Chapter 3, section 3.4.1.

Facies E: Unburrowed to moderately burrowed undulating fine-grained, scoured sandstone

Lithology and Sedimentary Features: Facies E ranges from very fine-grained to upper fine-grained, well-sorted sandstone, with rare occurrences of medium-grained sandstone. On average, the bed thickness is roughly 1 meter, but can vary between 30 centimeters to massive appearing beds up to 2.5 meters. Locally, finely bedded zones occur, with individual bed thickness less than 10 centimeters. Like Facies D, Facies E is characterized by a gentle curvature of the bedding, but the concave-upward is preferentially preserved, and the concave-downward is typically fully eliminated by erosion of the overlying bed (Figure 2.8 A, B). The curvature of the bedding, although typically more obvious than in Facies D, is generally low amplitude, with wavelengths in excess of 1 meter. Well-rounded, symmetrical appearing ripples are also sometimes preserved (Figure 2.8 C, D). Overall, organic debris is rare (<5%), and localized occurrences of siderite cement are observed. Wood lag impressions, with apparently random orientations (Figure 2.8 E), can be identified along the basal surfaces of some beds, which are also scoured (Figure 2.8 F).

Very local occurrences of well-preserved internal stratification can be observed, but are not typical to this facies. Generally these beds are 50 centimeters thick. The internal stratification reflects small-scale troughs that scour into underlying thin beds of planar laminations (Figure 2.8 G, H).

This facies has the greatest thickness variation, ranging between 1 and 20 meters; it is typically found in more continual successions in the western part of the study area. Facies E can be identified

Figure 2.8

Facies E: Unburrowed to moderately burrowed undulating fine-grained, scoured sandstone

A. Well-developed, large-scale swales are the most common feature of Facies E.

B. The lack of lateral continuity of sandstone beds across the outcrop indicates the erosive nature of the basal bedding surfaces.

C. Locally, ripples mantle the tops of sandstone beds.

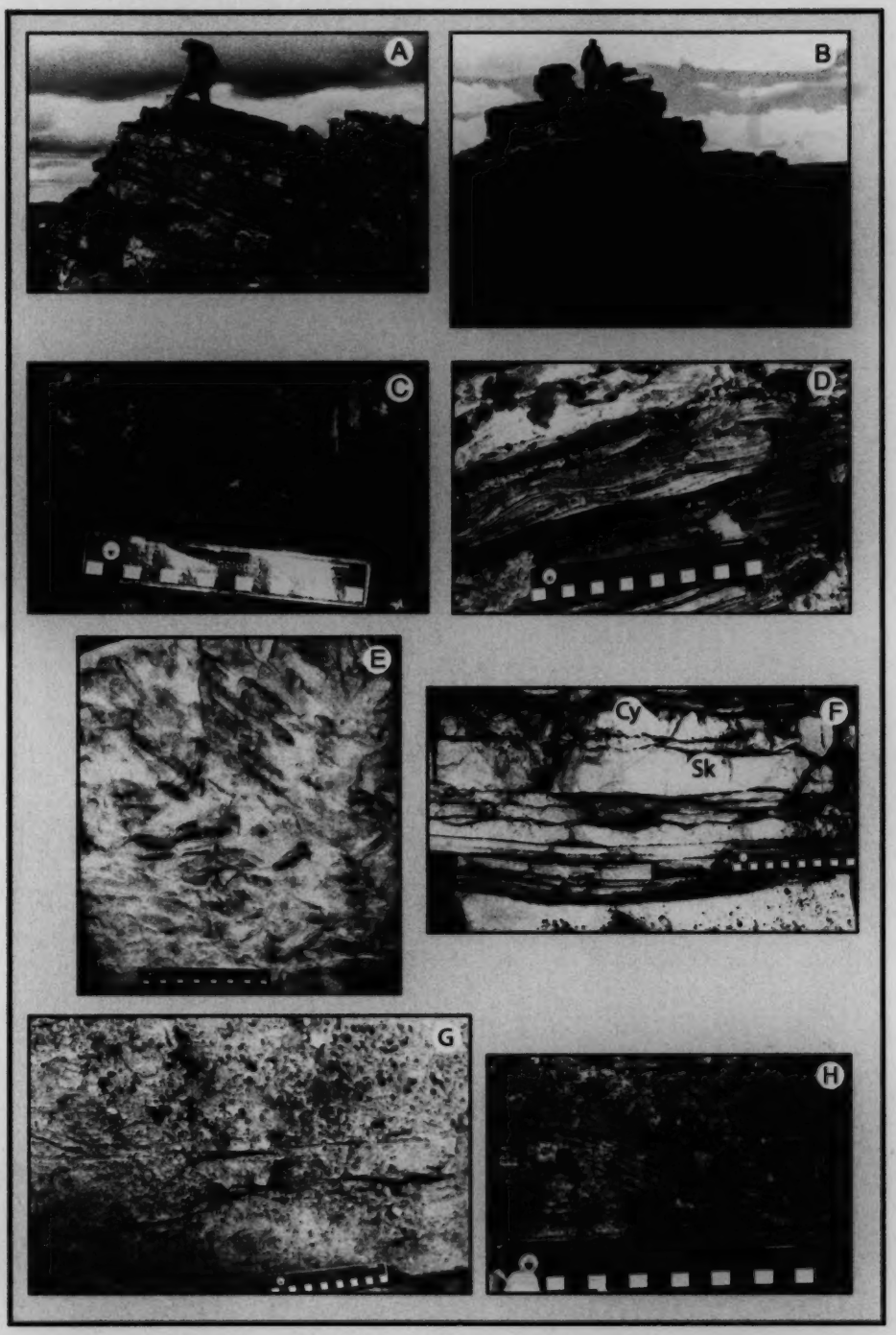
D. Well-developed ripple laminations.

E. Randomly oriented wood lag impressions are commonly observed along the undersides of bedding surfaces.

F. Scoured basal bedding surfaces are very typical of Facies E. *Cylindrichnus* (Cy) and *Skolithos* (Sk) traces are highlighted.

G. Local occurrences of well-preserved small-scale internal stratification. The sedimentary structures are interpreted as small migrating dunes and inter-bedded planar stratification, suggesting fluctuating hydrodynamic conditions.

H. Close-up of sedimentary structures shown in G.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in essentially all of the described sections, therefore being the most common facies within the study area. This facies is typically associated with Facies D, where it is usually deposited directly on top of it. The contact between Facies D and E is gradational.

Ichnology: The burrowing intensity ranges from absent to moderate, but overall this facies shows rare occurrences of trace fossils, with a relatively low diversity of forms. Where observed, the ichnofossil assemblage includes *Skolithos*, *Arenicolites*, *Cylindrichnus*, and *Palaeophycus* (Figure 2.8 F).

Interpretation and Discussion: Facies E is interpreted to contain swaley cross-stratification (SCS). The gentle curvature of the bedding is the fundamental feature, where the concave-upward (swale) is preferentially preserved and the concave-downward (hummock) is typically removed by the down cutting of the overlying bed. Duke (1980; *in* Duke 1985) informally introduced the term "swaley cross-stratification" to describe a type of HCS where the swales were present but the hummocks were rare or absent. Leckie and Walker (1982) provided a more formal definition of the term, stating that SCS consists of a series of superimposed concave-upward shallow scours, essentially the same as the swales of HCS. SCS should not be confused with trough cross-stratification, as troughs are generally narrower and deeper, and commonly associated with angle-of-repose cross-stratification (Leckie and Walker 1982).

Within the swaley beds of Facies E, it is possible to find a few concave-downward layers, supporting a genetic link between the formation of HCS and SCS, and supporting that SCS is a storm-dominated bedform (Leckie and Walker 1982). Leckie and Walker (1982) suggested that SCS originates in shallower water than HCS, and probably shallower than fair-weather wave base. This suggestion stemmed from the observation that in prograding sequences, SCS (when present) typically overlies HCS, which was thought to be deposited between storm and fair-weather wave base. This observation by Leckie and Walker (1982) is somewhat applicable to the Aklavik Formation, as Facies E is always found gradationally overlying Facies D, therefore representing deposition in shallower water, specifically the upper shoreface. However, Facies D, as previously mentioned, is visible as deposits both below and above fair-weather wave base; a difference in bedform style distinguishes the two types (see Facies D, Interpretations).

The defining characteristics of this facies, which allowed for the identification of SCS, are the undulating beds, frequent scour surfaces, and the preservation of swales and removal of hummocks. Frequent wood lag impressions preserved along the underside of bedding suggest abundant organic debris was transported with storm surges.

More energetic and frequent storms, as well as the combination of a shallower water depth, would allow for the amalgamation of storm deposits and hence the preservation of SCS (Duke 1985). These factors are interpreted to have contributed to the shift from HCS to SCS in the Aklavik Formation. Persistent storms resulted in nearly continuous reworking and removal of most of the record of fair-weather deposition. Furthermore, continuous sedimentation would allow for SCS formation, as opposed to episodic sedimentation, which results in the type of HCS described as inter-bedded lithologies (Duke 1985).

Overall, Facies E records deposition that dominantly reflects the influence of storm currents. Locally, there are beds that display well-preserved internal stratification, interpreted as small dune, or megaripple, migration (the formation of this structure is discussed in greater detail in Facies I Interpretations). From the presence of these small bedforms, it can be deduced that sedimentation under fair-weather conditions was possible, but rarely preserved in this overall storm-dominated setting.

The characteristics of the trace fossil assemblage of Facies E are similar to Facies D, but even lesser degrees of bioturbation are observed, with many beds void of traces. MacEachern and Pemberton (1992) indicate that this is typical of environments that are subject to high energy and therefore abundant reworking of the sediment by waves. It is not unusual for several meters of this facies to lack biogenic activity in these settings, which is a very typical of Facies E. Similar to Facies D, opportunistic species are represented by *Skolithos* and *Arenicolites*, reflecting that only the deepest penetrating traces were preserved below the scour surfaces created by successive storms.

Facies F: Planar-bedded, fine-grained sandstone

Lithology and Sedimentary Features: The grain size for Facies F is dominantly fine-grained, but ranges between very fine- to medium-grained sandstone. The bed thickness is variable, ranging between finely bedded to superficially massive in appearance, but is commonly between 20 centimeters and 1 meter (Figure 2.9 A, B). The more massive beds range in thickness between 1.5 and 2 meters. They appear massive because their internal stratification is unobservable, due to poor exposure. This facies is distinguished by the preservation of generally planar, non-erosive bedding contacts (Figure 2.9 C), with many beds lacking any observable internal stratification. Organic detritus is rarely observed; locally there are possible preserved impressions of wood fragments, and rare amounts of siderite cement. Ripple laminations are uncommon, but where present, show well-rounded ripple crests (Figure 2.9 D). Locally, organic detritus highlights internal stratification. In these instances, erosionally based beds of ripples can be seen inter-bedded with very thin beds of planar laminations (Figure 2.9 E). This is the only preserved occurrence of such dynamic flow conditions within this facies, specifically due to the poor visibility of much of the outcrop.

Facies F is closely associated with Facies G and it is often difficult to distinguish between the two. Across the study area, Facies F is commonly observed, ranging in thickness between 1 and 8 meters.

Ichnology: The burrowing intensity of Facies F is typically minimal to non-existent. Where observed, *Cylindrichnus* is the predominant trace identified. In very localized areas, the intensity of bioturbation is dramatically higher (moderate to intense), with an assemblage consisting of *Cylindrichnus*, *Skolithos*, *Planolites*, and *Palaeophycus*. Typically, bioturbation is most commonly found near the tops of the sandstone beds.

Interpretation and Discussion: The interpretation of Facies F is highly speculative. In many localities, the poor preservation of internal stratification of individual beds leads to the uncertain identification of outcrop as Facies F. Typically, only the major contacts between bedsets are identifiable as planar, but are characterized by a lack of observable stratification within each

Figure 2.9

Facies F: Planar-bedded, fine-grained sandstone

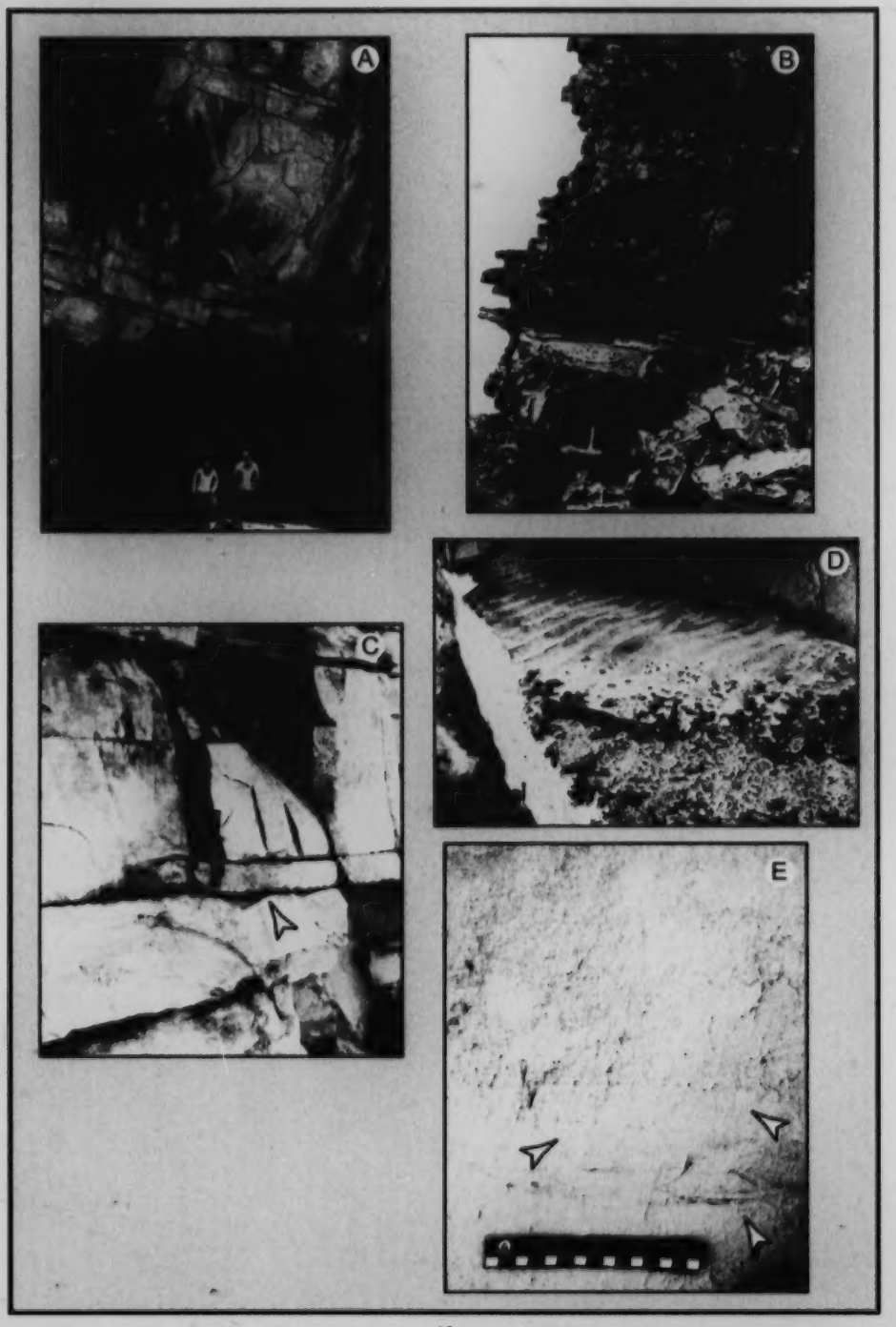
A. Typical superficially massive nature of the outcrop.

B. Bedding thickness is commonly between 20 cm and 1 m. The more bioturbated zones, as pictured here, are typically not as thick.

C. Planar, non-erosive bedding contacts, which are frequently rippled are characteristic.

D. Well-rounded ripples; this particular example is an anomalously well preserved bed.

E. Rare, local occurrences of internal stratification. Sedimentary structures are highlighted by fine organic debris and are interpreted to represent brief periods of variable flow conditions. Erosionally based beds of wave ripples are truncated by low-angle planar laminations, which are then truncated by trough cross-stratification, indicative of migrating small dunes.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individual bed. The lack of grain size contrast in the sandstone contributes toward the difficulties in identification of sedimentary structures, resulting in superficially appearing massive sandstone beds. Other features of the outcrop, specifically stratigraphic positioning, then become important in determining plausible explanations for deposition. It is possible that variable conditions contributed to the deposition of Facies F, and that no one single set of environmental conditions resulted in all of the planar-bedded sandstone observed in the study area.

The relationship between Facies F and Facies E and G (see Facies G Interpretations) greatly supports that, at least at some localities, deposition of this facies was somewhat influenced by storms or their waning currents. Based on the stratigraphic relationship Facies F displays with these previously mentioned facies, it is interpreted that overall, deposition took place in the shoreface, more commonly the upper shoreface.

It has been suggested that most of the rock record of the nearshore zone records deposition during storm conditions (Kumar and Sanders 1976; Saunders pers. comm. 2003). Yet the effects of storms in shallower water depths, such as the upper shoreface, are generally poorly understood (Saunders pers. comm. 2003). This is typically due to the physical difficulties associated with studying storm currents in modern settings. It is possible that even mild discrepancies in the shoreface, for example topographic variations of the slope, could cause storm currents to create conditions suitable for SCS deposition with isolated conditions suitable for differing deposits, such as thicker planar beds (Saunders pers. comm. 2003).

The very low density of bioturbation in Facies F suggests three different scenarios, or a combination of any of the three: a) deposition and bioturbation may have taken place under such high energy conditions that the burrows were rarely preserved due to reworking by currents; b) the uniform composition and grain size of the sandstone prevents identification of burrows that are unlined; c) harsh ecological conditions existed, and were not conducive for the survival of burrowing organisms. It is possible that all three contributed towards the sparse level of bioturbation associated with Facies F, yet the overall consistent grain size, as well as the lack of mud, contribute the most to low level of observable burrows.

Facies G: Wavy-bedded, homogeneous, fine-grained sandstone

Lithology and Sedimentary Features: The grain size of Facies G is dominantly fine-grained, with variability between very fine- to medium-grained. The sandstone is well sorted, and commonly appears structureless. Bed thickness can reach a maximum of 2.25 meters, but is commonly between 25 centimeters and 1 meter. Broad, low amplitude undulating beds of sandstone characterize Facies G (Figure 2.10 A, B, C). Ripples appearing well rounded and generally symmetrical to somewhat asymmetrical in profile are frequent (Figure 2.10 D, E). Finely comminuted organic detritus commonly accentuates ripple lamination. Local occurrences of wood lag impressions and siderite cementing are rare. Due to the nature of the poorly preserved outcrop, much of the rock in the study area is lumped into this facies; therefore Facies G is very common across the entire study area.

Figure 2.10

Facies G: Wavy-bedded, homogeneous, fine-grained sandstone

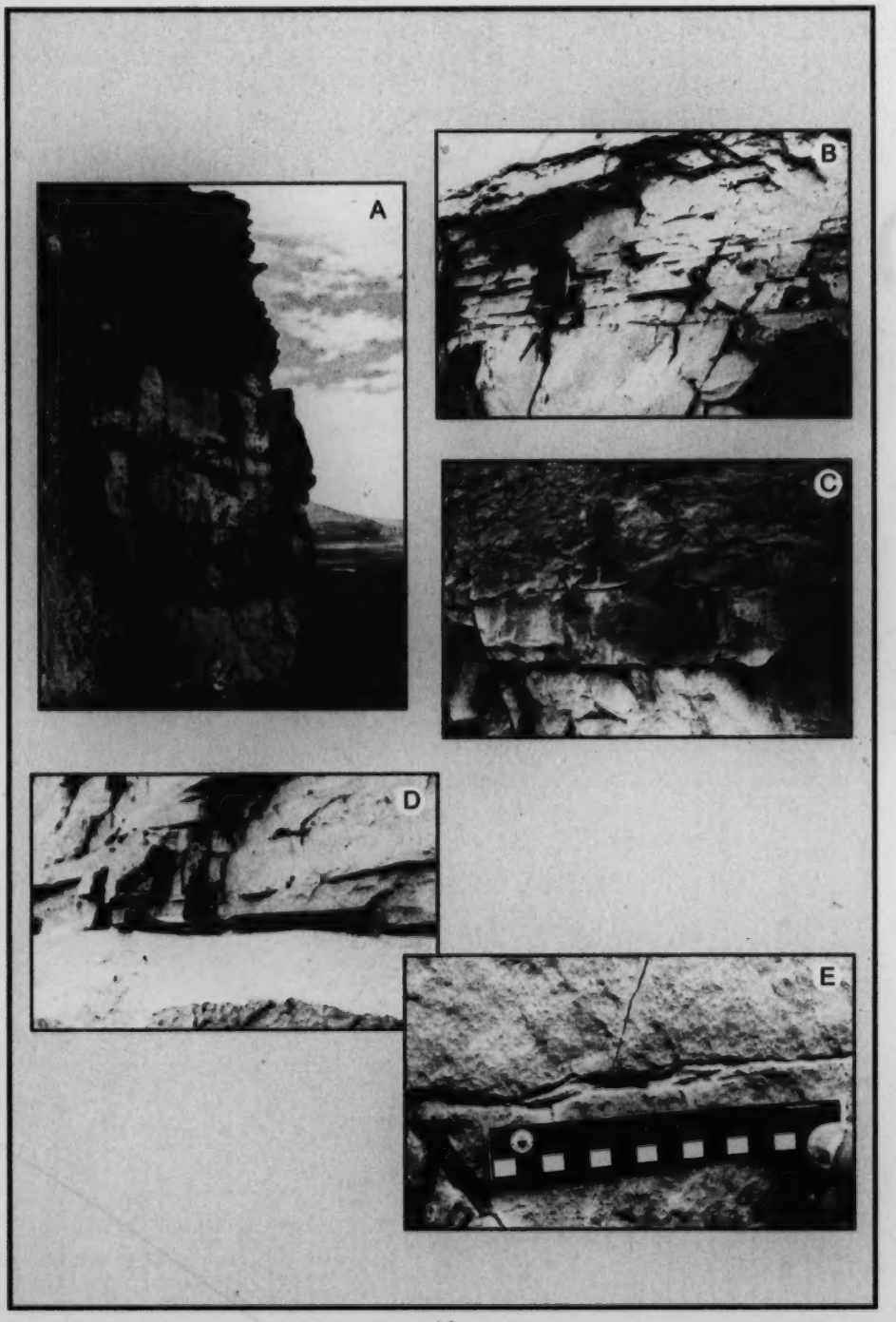
A. Variable bedding thickness of sandstone beds of Facies G, ranging between a few cm's to under a meter. Roughly 4 m of section is shown in this photo.

B. Very low-angled wavy sandstone beds are characteristic.

C. Very broad, low-angled wavy bedding contacts.

D. Well-rounded ripples preserved along upper bedding surfaces.

E. Small migrating ripples.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The thickness variation of Facies G is between 1 and 7 meters, but is characteristically less than 5 meters. The boundary between this facies and Facies F is very gradational; whether the rock is identified as planar or wavy is predominantly dependent on the quality of the outcrop. Facies G is also commonly inter-bedded with sandstone beds of Facies D and E.

Ichnology: Overall, bioturbation intensity within Facies G is rare to absent. The most common traces, where observed, consist of *Planolites*, *Palaeophycus*, and *Cylindrichnus*, with rare *Skolithos*.

Interpretation and Discussion: The gently undulating bedding contacts and abundant ripple laminations with rounded crests reflect deposition within an overall wave-dominated setting. Facies G represents deposition on the shoreface. It is most commonly observed inter-bedded with Facies E (interpreted as upper shoreface storm beds), therefore supporting that Facies G predominantly corresponds to upper shoreface deposits.

In the better-exposed localities, where the wavy or undulose nature of the bedding contacts is well developed, a more detailed hypothesis for the deposition of this facies can be suggested. Quasi-planar laminations (QPL) are known to be closely connected with planar beds of the lower shoreface or upper offshore, as well as storm deposits such as HCS and SCS (Arnott 1993), and it is speculated that local occurrences of Facies G represent such bedforms.

QPL was first identified and described by Arnott (1987; 1993). These sedimentary structures are distinguished by gentle undulating laminations that show evidence of vertical aggradation, but no lateral accretion, with spacing of undulations ranging from a few tens of centimeters to a few meters, and heights rarely exceeding several centimeters (Arnott 1993). An idealized succession of QPL includes three parts: a) a sharp, undulatory basal contact, sometimes scouring into underlying beds; b) a thick interval of quasi-planar laminations; and c) a thin rippled cap. The development of QPL begins with an increase in both unidirectional and oscillatory flow components (and therefore a feature of combined flow) during building storm conditions. Following the height of the storm, where scouring may or may not take place, the onset of sedimentation results in QPL. The capping rippled unit develops during waning flow energy, reflecting deposition under overall waning storm conditions. Some of the thick beds of Facies G (<5 meters) that are closely associated with SCS beds of Facies E are interpreted as amalgamated beds of QPL. The development of aggrading beds, with lack of significant lateral accretion, also reflects the abundant sediment supply that was available during Aklavik time.

Overall, QPL beds are interpreted to indicate single-event deposition under high-energy, combined flow conditions, where net sediment transport is in an offshore direction (Arnott 1993). Where beds of Facies G demonstrate a strong relationship with deposits of Facies E (and less frequently Facies D), an interpretation of high-energy storm deposition in the shoreface is inferred. Where this relationship is observed, typically deposits of Facies G sit gradationally overtop of SCS beds, suggesting that the fluctuation of storm conditions allowed for continued deposition, but of a different bedform style. This reflects the dynamic nature of storm currents, and that not all storm deposits associated with the shoreface are preserved as SCS or HCS beds. Other stratification types

generated by high-energy oscillatory flows, such as HCS and SCS, should be anticipated interbedded with QPL, depicting sedimentation under different current intensities (Arnott 1993).

The trace fossil assemblage of Facies G is very similar to the previous facies, and holds a similar interpretation (see Facies F Interpretations). The vertical *Cylindrichnus* and *Skolithos* that are locally observed reflect burrowing by opportunistic trace makers that were able to survive in the relatively high-energy conditions, associated with storms (Frey and Pemberton 1984; Pemberton *et al.* 2002). With the subsequent return to quieter conditions, traces such as *Palaeophycus* were created by organisms that were typical to the environment, resulting in an overlapping of tiered ichnofacies (Pemberton *et al.* 2002).

Facies H: Trough cross-stratified, medium-grained sandstone

Lithology and Sedimentary Features: The grain size of this facies is typically medium-grained, but ranges between upper fine to lower coarse. The sediment is moderately sorted with rare organic debris preserved. Facies H is characterized by trough cross bedding. This stratification can be further described as curved and tangential to the underlying basal surface (Figure 2.11 A - C). These curved laminations infill elongate, erosionally scoured troughs that in some orientations display a series of well developed, upward truncated arcs (Figure 2.11 D). Multiple sets of troughs suggest stacking of this bedform, allowing for up to 8 meters of this facies to be preserved in any given section. The depth of each individual trough is varied, but averages 30 centimeters. Locally, a decrease in the trough size is visible moving up section (Figure 2.11 D). Wood impressions are commonly preserved along the basal, scoured surfaces (Figure 2.11 E). Somewhat asymmetrical ripple development is occasionally visible along the tops of beds (Figure 2.11 F). In some places, this ripple lamination increases in size, and is better described as tabular cross lamination (Figure 2.11 G). Rounded, symmetrical appearing ripples are also present. Siderite cementing is locally prevalent.

At some localities, well-exposed evidence for a significant, irregular erosional surface can be observed, down cutting into Facies E (Figure 2.11 H). This facies is not widespread across the study area; it is only present in the eastern regions, where it ranges between 1 and 8 meters, and appears to thicken towards the east.

Ichnology: No trace fossils were observed.

Interpretation and Discussion: Facies H is interpreted as channel fill deposits associated with a fluvial or distributary-like channel of a delta. This facies marks a shift from the typical shoreface complex that characterizes the Aklavik Formation. The abundant trough cross-stratification that characterizes this facies reflects the migration of numerous dunes or small bars along the base of the channel. The presence of both symmetrical and asymmetrical ripples, interpreted as wave and current ripples, respectively (Harms *et al.* 1975), reflect the collective interaction of marine and fluvial processes responsible for modifying the sediment. Isolated occurrences of tabular cross-stratification are thought to represent migration of sand waves; this shift from current ripple to sand wave is the consequence of an increase in velocity of the flow (Harms *et al.* 1975). The initial pulse

Figure 2.11

Facies H: Trough cross-stratified, medium-grained sandstone

A. Trough cross-stratification characteristic of Facies H. View is a somewhat oblique longitudinal section.

B. Close-up of A; well-developed curved laminations that are tangential to the basal surface.

C. Organic debris as well as coarser grained sand highlight the internal stratification.

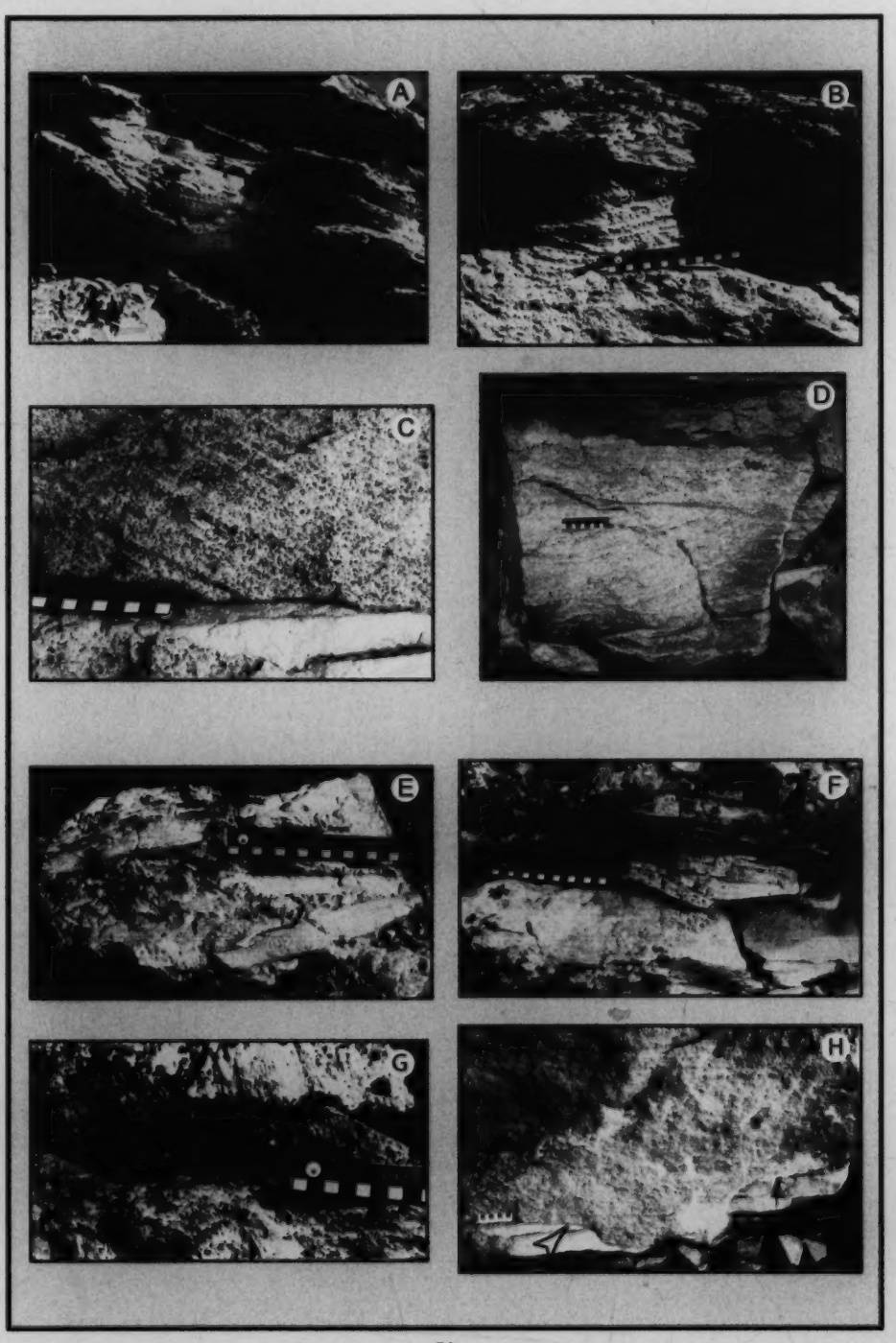
D. A cross-sectional view through a stacked succession of scoured troughs. Moving upwards, a decrease in trough size can be noted.

E. Wood impressions, which are commonly found as lag deposits along the underside of bedding contacts.

F. Large ripples observed along the tops of some cross-stratified beds.

G. Locally, high-angle tabular cross laminations were observed, and interpreted as migrating sand waves. The presence of dunes as well as sand waves and ripples suggests that the flow conditions were not static, but were dynamic.

H. An irregular, erosional surface, as highlighted here, was observed locally. The surface was evidence that Facies H had incised into Facies E, interpreted as upper shoreface deposits.


A
B
C
D
E
F
G
H

of sediment, possibly associated with each ensuing storm event, deposited organic and wood debris in the form of lags along the bounding surfaces of trough cross-stratified bedsets.

In the most landward outcrop localities, Facies H incised into the upper shoreface deposits of Facies E, creating an irregular erosional basal surface that demarcates this facies as the product of channel deposition. Uncharacteristically, the channel fill deposits lack any fine-grained material. This is presumably a factor of the marine influence being greater than the fluvial, a result of the high wave energy that the shoreface regularly experienced. The waves would have reworked the debouched sediments, winnowing out the fine grain material and carrying it offshore in a suspended cloud (Suter 1994). Also, it is possible that the sediment supply was predominantly coarser grained to begin with. Wright (1985) observes that sandy channel fills, exhibiting pronounced cross bedding, are associated with rivers that transport a high percentage of bed load. The shoreface complex that comprises the Aklavik Formation is, overall, abnormally thick, suggesting that what fluvial input existed was responsible for the transport of a great amount of sediment. This can be seen in the stacking of trough cross-stratified bedsets, resulting in a total thickness of 8 meters of Facies H. The bedsets demonstrate a decrease in trough size upwards, suggesting that either the sediment load began to diminish over time, or that the flow could only handle so much suspended load before the channel became sediment choked.

Variable salinity conditions are commonly associated with deltaic settings, due to the intermixing of fresh and marine water. The consequence is an imbalanced, highly fluctuating water chemistry that is typically not favorable for a diverse burrowing fauna (Pemberton and Wightman 1992). This coupled with high energy associated with frequent storms, high sediment load with possible turbid waters, and continuously migrating bedforms, created a setting that was ecologically challenging for even the most opportunistic species to survive. Therefore, the interpretation of Facies H as distributary channel fill is supported by the lack of trace fossils.

Facies I: Small-scale trough cross-stratified, fine-grained sandstone

Lithology and Sedimentary Features: Facies I is dominantly fine-grained, with very rare occurrences of pebble stringers. Small-scale, wedge-shaped bedforms distinguish this facies, with internal stratification showing well-developed tangential laminae, or clinoforms (Figure 2.12 A); the lamination dip ranges between 17 and 30 degrees. Typically, these structures overlap one another, creating laterally extensive beds (Figure 2.12 B). Although the bounding surfaces are sharp, they do not appear to be erosive. The apparent height and length, when it can be roughly estimated, are 20 and 80 centimeters, respectively. These bedforms appear to be stacked successively on top of each other, resulting in a total bed thickness of approximately 2 meters in some places (Figure 2.12 C). Thin beds of apparently planar laminations highlight the bedding contacts; these beds are preferentially cemented, characterized by a light orange stain, presumed to be siderite (Figure 2.12 D). Ripples are frequent, with the most common location of preservation being the lee side of the larger bedforms; the exact ripple style is difficult to distinguish.

Facies I is most commonly observed in the eastern region of the study area, where it ranges between 2 to 6 meters in thickness, and also locally in large, non-*in situ* boulders.

Figure 2.12

Facies I: Small-scale trough cross-stratified, fine-grained sandstone

A. Wedge-shaped, stacked clinoforms characterize the small-scale trough cross-stratified beds of Facies I.

B. The bedforms commonly overlap, creating laterally extensive beds, as shown here. These structures are interpreted as continuously migrating small dunes.

C. Typically the beds of small-scale trough cross-bedding are stacked successively, resulting in thick packages. Roughly 2.5 m of section is shown here.

D. Thin, apparently planar laminations show preferential cementing by siderite (orange color). These planar laminations highlight the bedding contacts, and can also be seen in C.

E. The upper portion of Facies I is typically characterized by an intensely bioturbated zone. Monospecific assemblages of *Diplocraterion* (Di) are characteristic; *D. habichi* are shown here.

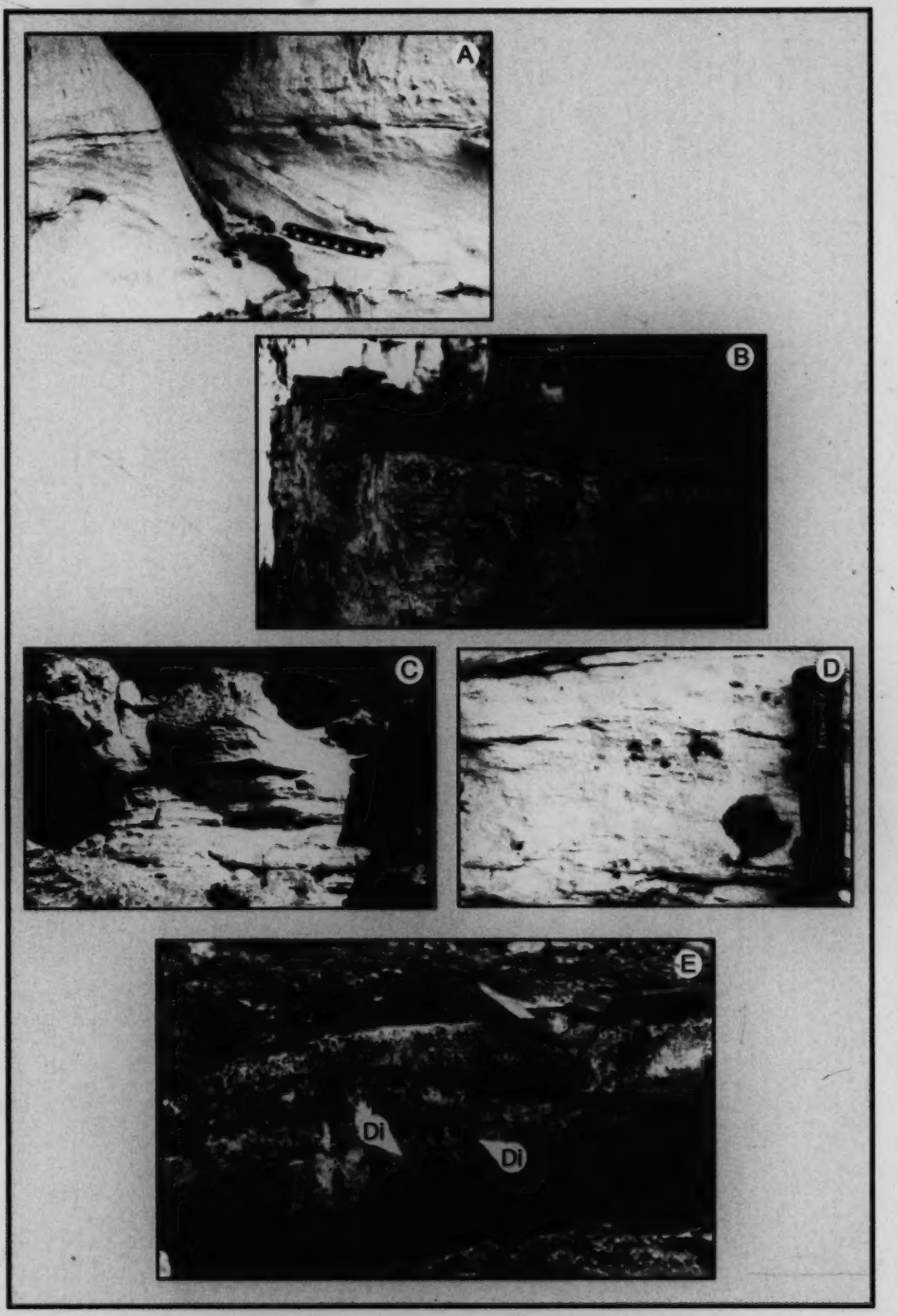

A
B
C
D
E
Di
Di

Figure 2.13

Facies I (continued)

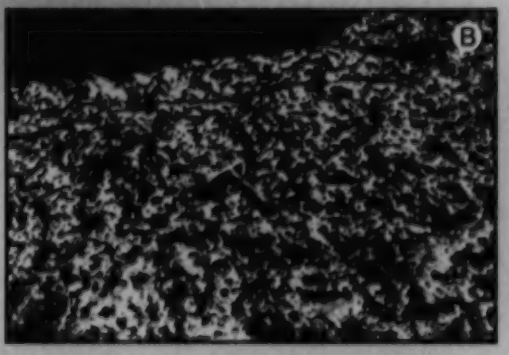
A. Dense assemblages of *Diplocraterion parallelum* are classified as *Glossifungites* surfaces, which can be observed locally.

B. The localized surface identifed as a *Glossifungites* surface, comprised of a dense assemblage of *D. parallelum*. The *Glossifungites* surface is important for the emphasis of a depositional hiatus, however it is not temporally significant, and therefore not useful for correlation purposes.

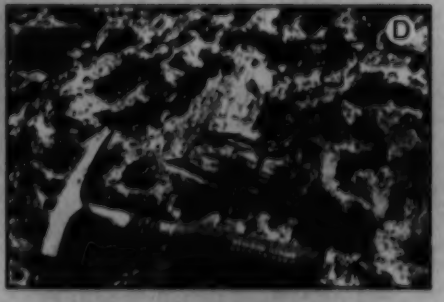
C. Some of the burrows have very thin mud linings; these linings appear to be associated more with the *D. habichi* assemblage (pictured in Figure 2.12 E).

D. Impressions of wood and other organic debris are closely associated with the *Glossifungites* surface. The preserved impressions are evidence that the substrate was not soft and soupy at the time of colonization, but was somewhat cohesive. The cohesive or firm state of the substrate is what defines the surface as a *Glossifungites* assemblage.

A
DI
DI


B

C
DI
DI


D

Ichnology: Burrows are generally absent in this facies, except in the upper 20 centimeters, where moderate to intense levels of well-developed beds of monospecific *Diplocraterion* can be observed (Figure 2.12 E; Figure 2.13 A, B). These *Diplocraterion* sometimes have thin mud linings, and are locally associated with the facies (Figure 2.13 C). Both *Diplocraterion habichi* and *D. parallelum* species can be identified. Associated with these densely bioturbated horizons are impressions of wood and other organic debris (Figure 2.13 D).

Interpretation and Discussion: The wedge shaped bedforms that characterize Facies I are interpreted as small dunes that continually migrated to produce trough cross-stratification. Dunes have also been described under the term mega-ripples (Reineck and Singh 1980). This facies was deposited under fair-weather conditions in relatively shallow water. Typically, dunes are not strongly dependent on flow depth, yet Harms *et al.* (1975) suggested that a minimum water depth could be estimated by doubling the height of the bedform. Following this idea, the minimum flow depth during deposition of Facies I would have been 30 centimeters, but was presumably somewhat deeper. These beds of trough cross-stratification are intermittently inter-bedded with thin beds of very low angle, planar-tabular cross-stratification. Examples of this distinctive bedding style can be observed locally, where siderite cement highlights the thin beds of planar-tabular cross-stratification.

Facies I represents reactivation of the upper shoreface, as a result of trangression. These sediments can be thought of generally as upper shoreface deposits, for ease in communicating the stratigraphic positioning and water depth associated with deposition. However, it is important to note that these deposits are not laterally equivalent to the upper shoreface deposits of Facies E. As further discussed in Chapter 3, sections 3.2.2 and 3.6, Facies I represents sedimentation during initial transgression, rather than regression, implying that the environmental conditions had significantly changed between deposition of Facies E and I. Sediments underlying Facies I (i.e. Facies D, E, H) were sourced from deltaic input to the coastal setting. With the onset of transgression, deltaic sedimentation came to an end, or at least was largely minimized relative to earlier times. Transgressive waves gave rise to sediments of Facies I being sourced from the reworking of distributary mouth bars and channel deposits. Deposition of these reworked sediments reflects fair-weather conditions, somewhat atypical of the underlying facies, which imply dominance by storm influence. Fair-weather conditions were more typical during Facies I, with the transition to a transgressive environment.

The restricted outcrop data available for this facies somewhat limits the possible interpretations for the depositional environment. It has already been suggested that Facies I resulted from the migration of dunes across a shallow water upper shoreface environment during fair-weather conditions, where sediment was sourced from reworked older deltaic deposits. Continuing on this idea, it can be speculated that Facies I represents part of a more complicated transgressive shoreface system. With the onset of transgression, the influence of storms was presumably dissipated, allowing for tidal effects to be preserved during fair-weather conditions. Therefore, it is suggested that Facies I may in fact represent tidal deposition within a shoal of a tidal inlet.

Submergence of a coastal setting can result in barrier island formation (Reinson 1992), and it is speculated that transgression of the Aklavik shoreline would have created this type of system. Tidal

inlets form between two barrier islands, and are dominated by tidal rather than wave processes, even in settings that are typically wave-dominated, such as that for the Aklavik Formation. Frey and Howard (1988) examined inlet shoals associated with Holocene barrier islands off the coast of Georgia. Within the highest energy, intertidal to shallow subtidal zone, their findings greatly resembled observed characteristics of Facies I. Sediments consisted predominantly of clean, well sorted, fine to medium grained sand. Distinguishing sedimentary structures included trough cross-bedding (interpreted as migrating swash bars, dunes, and sand waves), small-scale wave, current, and combined flow ripples, and local expanses of planar, parallel laminations. The close resemblance of characteristics of Facies I and inlet shoal deposits identified by Frey and Howard (1988) leads to the interpretation that this facies denotes deposition under tidal influences within a tidal inlet. The absence of clay drapes and reactivation surfaces, common to tidal settings, suggests that the dunes were migrating nearly continuously, an attribute of fair-weather conditions (Wignall *et al.* 1996). The lack of preserved depositional environments associated with this barrier island system is a result of the cannibalization effect of transgressive waves.

The continuously migrating bedforms of Facies I present a major ecological challenge to endobenthic organisms (Pemberton *et al.* 2002), and the overall lack of traces in Facies I reflects this. Bioturbation is therefore restricted to the upper portion of Facies I, where well-developed beds of *Diplocraterion habichi* and *D. parallelum* can be seen. These monospecific assemblages are interpreted as part of the substrate-controlled *Glossifungites* ichnofacies. This surface can be observed in the eastern region of the study area only, in localized occurrences.

The *Glossifungites* ichnofacies was originally defined by Seilacher (1967), and described as a primarily littoral assemblage of trace fossils associated with a cohesive, non-shifting substrate. Frey and Seilacher (1980) limited this definition to include only firmgrounds present in marine environments. The *Glossifungites* trace fossil assemblage has several diagnostic characteristics (Seilacher 1964; Frey and Seilacher 1980; Pemberton and Frey 1985; MacEachern *et al.* 1992; Pemberton *et al.* 2002), which have been summarized in Table 2.1. Within the marine setting, the *Glossifungites* ichnofacies is environmentally wide ranging, but is restricted to firm, but unlithified, substrates (Pemberton *et al.* 2002). A substrate is made firm through the process of dewatering, which can occur either by subaerial exposure and desiccation, or by burial, compaction, and exhumation due to erosion (Pemberton and Frey 1985; Gingras *et al.* 2001; Pemberton *et al.* 2002). This latter process typically exposes the firmground to colonization under marine conditions, creating potentially important surfaces. These surfaces, when areally and temporally significant, can be useful for genetic-stratigraphic interpretation, due to their link with autocyclic or allocyclic base level changes in marginal marine environments (Pemberton and Frey 1985; MacEachern *et al.* 1992; Pemberton and MacEachern 1995; Gingras *et al.* 2000; Pemberton *et al.* 2002). The presence of a *Glossifungites* suite indicates that a depositional hiatus occurred between the erosional event and sedimentation of the overlying unit (Pemberton *et al.* 2002).

The identified *Glossifungites* assemblage of Facies I is recognized only locally, specific to the eastern region of the study area. Where it is well developed and laterally extensive across the outcrop, the assemblage is composed of a mixed suite of *D. parallelum* and *D. habichi*, with *D. parallelum* dominating. In a different location, a monospecific assemblage of *D. habichi* was recognized; this assemblage is part of a less aerially extensive surface, and therefore presumably

not as significant. The recognition of this particular surface as a *Glossifungites* assemblage is much less obvious. However, the close proximity to other identified *Glossifungites* surface, as well as the stratigraphic positioning of the *D. habichi* surface (i.e. along the top of the Aklavik Formation) allow it to be interpreted as part of the overall firmground suite. It is possible that in the particular region where the *D. habichi* trace makers colonized the sand, the substrate may not have been as firm, a result of differences in compaction and dewatering across the study area.

The recognition of the *Glossifungites* assemblage identified locally at the top of Facies I demarcates an important surface. First, the presence of the firmground ichnofacies implies a depositional hiatus. Second, this phenomenon can be correlated between certain outcrops over a minimum of two kilometers, indicating that it is somewhat temporally and areally significant. As a result, this surface assists in the interpretation that transgression resulted in cessation of deposition of the Aklavik Formation (see Facies J Interpretations; Chapter 3, sections 3.2.2 and 3.6).

Facies J: Poorly sorted, erosionally-based, coarse-grained sandstone

Lithology and Sedimentary Features: Facies J is comprised of sandstone with variable grain size, ranging between upper medium- to lower coarse-grained. The sediment is moderately to poorly sorted, and appears in hand sample to be more lithic than the common Aklavik sandstone facies, which are typically quartz dominant, as described in Chapter 4. The basal surface of this facies is erosional (Figure 2.14 A). Wood debris and finer organic material, as well as mud clasts up to 3 centimeters in length, are all common (Figure 2.14 A). The occurrence of bioclastic material includes bivalve imprints and possible shell fragments.

The thickness of this unit is variable, ranging between 2 and 10 centimeters. This inconsistency appears to be a function of the underlying topography at the time of deposition. Facies J weathers differently compared to the underlying facies (i.e. Facies I); generally it appears less blocky and less cemented. This facies is always observed at the top of the Aklavik sandstone outcrop (Figure 2.14 B), and is only visible locally.

Ichnology: No trace fossils were identified.

Interpretation and Discussion: Facies J is interpreted as a lag deposit, resulting from transgressive erosion of the shoreface. Pemberton and MacEachern (1995) interpreted these types of deposits as the proximal facies of transgressive erosion or ravinement processes, corresponding to the erosional remnants of a landward movement of the shoreface during erosional shoreface retreat. Overall, the main constituents comprising this facies are intra-formationally derived, supporting a genetic link between erosion of the substrate and emplacement of the lag deposit (MacEachern *et al.* 1992). The origin of the mud clasts, bioclastic, and organic debris is presumably related to the Aklavik Formation, originating possibly from deposited beds that were typically not preserved during this time, for example the foreshore or backshore environments.

The erosional surface on which the lag sits is interpreted to be a transgressive surface of erosion (TSE) (Bhattacharya and Walker 1991; MacEachern *et al.* 1992). This is equivalent to the ravinement and marine erosion surfaces of Nummedal and Swift (1987), the surface of initial

Figure 2.14

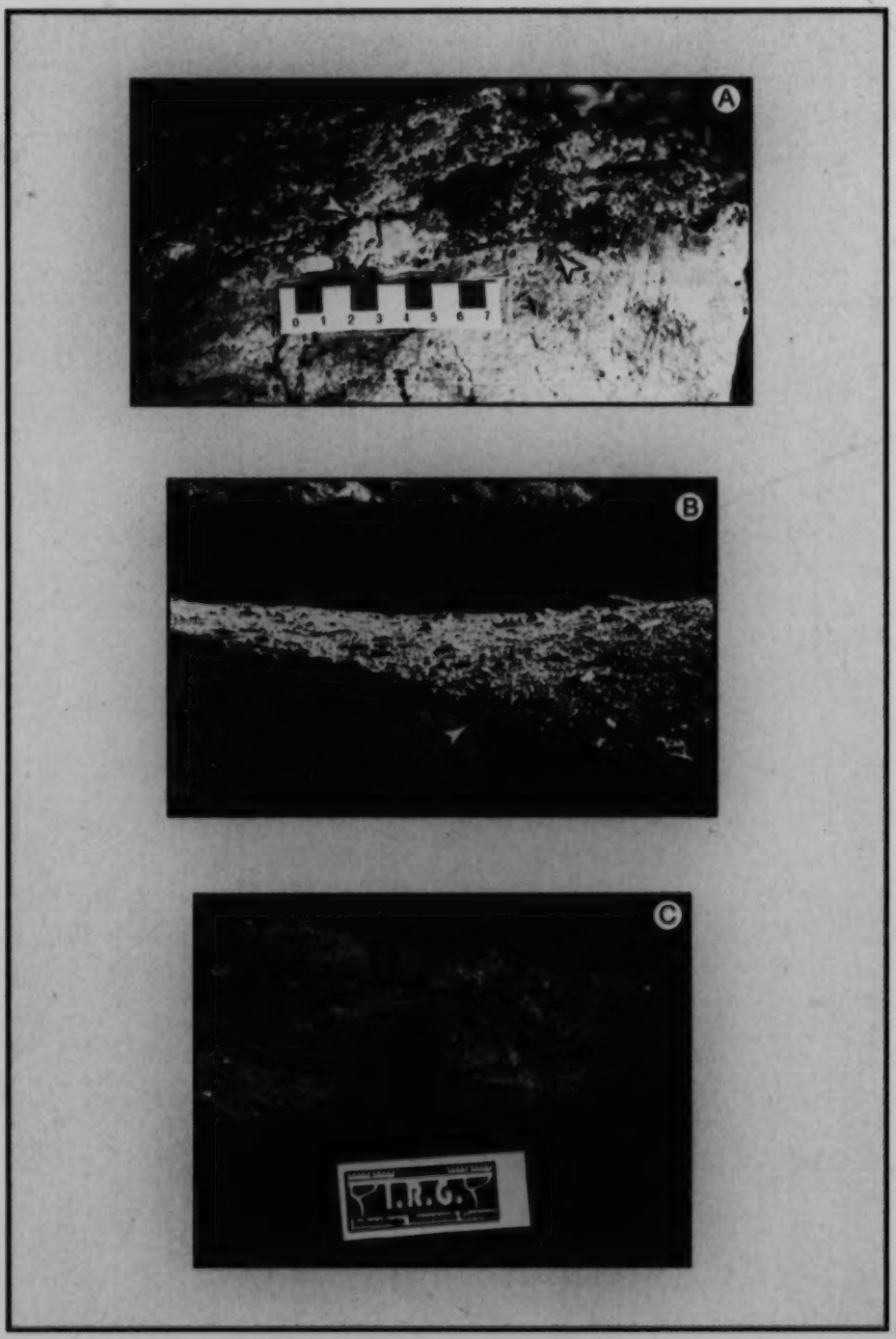
Facies J: Poorly sorted, erosionally-based, coarse-grained sandstone

A. Poorly sorted, coarse-grained sandstone of Facies J. Wood debris, organic matter, bioclastic material, and mud clasts (shown here) are all common components of this facies. The basal surface is irregular and erosional.

B. The top of outcrop of the Aklavik Formation is shown here; Facies J, when present, is always the capping unit. Here it overlies Facies I.

Facies K: Moderately bioturbated, very fine-grained sandstone with abundant mudstone

C. Facies K is very thin and only observed in rare occurrences, therefore it was not often described or photographed. Fine-grained sandstone with abundant muddy laminations characterize this facies.


A
0 1 2 3 4 5 6 7
B
C

transgression (IT) of Walker (1990), and the high-energy flooding surface of Pemberton and MacEachern (1995). It can be defined as a low relief, erosional surface that is cut by wave action and current processes, typically affecting the upper shoreface during transgression and associated erosional shoreface retreat (Reading 1996; Pemberton and MacEachern 1995). Commonly, these types of surfaces are discontinuous and limited spatially (Pemberton and MacEachern 1995). This is true of the TSE of the Aklavik Formation, which can be observed only in well-preserved localities in the eastern part of the study area. Therefore, the effectiveness of this surface for regional correlations is limited.

The existence of a depositional hiatus between the erosional event and emplacement of the lag is confirmed by the presence of the *Glossifungites* assemblage, identified as the firm ground ichnofacies colonizing the facies beneath the lag (see Facies I Interpretations). Firm-ground trace fossil assemblages are commonly associated with TSE, as the exhumation of the surface takes place within a marine or marginal marine setting (Pemberton and MacEachern 1995), which is typically more conducive for bioturbating organisms. Colonization of the exhumed surface post-dates erosion by transgressive waves, but occurs prior to significant deepening due to the impending relative sea level rise. These stratigraphic breaks in the rock record are easily mistaken for sequence boundaries without proper examination of the full facies succession (Nummedal and Swift 1987). The presence of a substrate-controlled trace fossil assemblage greatly assists with the recognition of the hiatus at the top of the Aklavik Formation. This is similar to the Albian Upper Viking Formation, of the Western Canadian Sedimentary Basin, where the identification of numerous TSE has been assisted by the recognition of a *Glossifungites* suite (Pemberton and MacEachern 1995).

It is important to note that the fill of the burrows of the *Glossifungites* assemblage does not consist of the same sediment as the transgressive lag. This implies that the event that deposited the lag was not the same one that eroded the upper portion of Facies I. Therefore transgression did not occur as a smooth change, but rather as a punctuated event that potentially created multiple erosive events due to transgressing waves.

Facies K: Moderately bioturbated, very fine-grained sandstone with abundant mudstone

Lithology and Sedimentary Features: This facies is dominantly comprised of very fine-grained sandstone with muddy laminations (Figure 2.14 C). Organic material is common, and is commonly concentrated within the linings of the trace fossils. Symmetrical appearing ripple laminations are present, accentuated by mud laminations.

This facies is typically very thin, generally less than 10 centimeters. Facies K is observed locally, and is always associated with the top of the Aklavik outcrop. It gradationally overlies Facies J, and is always found directly below Facies L, which sharply overlies Facies K.

Ichnology: Facies K consists of organic to mud lined, horizontal to sub-vertical trace fossils. Typically, the burrowing intensity is moderate. The ichnofauna assemblage is comprised predominantly of *Palaeophycus*, *Teichichnus*, and *Chondrites*.

Interpretation and Discussion: The interpretation for Facies K is limited due to its very localized occurrence and thin exposure. The primary sedimentary structure identified is interpreted to be wave ripples, although the influence of other current types cannot be ruled out. This, along with the abundance of very fine-grained sandstone and mudstone, and the degree of bioturbation and the trace fossil assemblage identified, suggest that Facies K was deposited within a relatively low energy, nutrient rich, fully marine environment (MacEachern and Pemberton 1992; Pemberton *et al.* 2002).

Relative to the facies that have been identified stratigraphically lower, Facies K appears to be deposited under very different conditions. The sedimentary structures suggest a lack of high energy, typical of the other upper facies of the Aklavik Formation, as well as slower sedimentation rates within deeper water. The identification of sub-horizontal to horizontal trace fossils that are typically associated with the *Cruziana* ichnofacies support this idea. Deeper water depositional conditions are also reflected by the association of Facies K with the facies found above and below. Facies K is always found directly above the lag deposit, identified as Facies J; this relationship leads to the interpretation that Facies K represents the distal deposits of the continuing transgressive erosion taking place farther landward (Pemberton and MacEachern 1995). Pemberton and MacEachern (1995) interpreted sediments found gradationally overlying transgressive lag deposits as the result of erosion of laterally equivalent, landward shorefaces; the material is then reworked and transported seaward by storms.

Facies K is situated gradationally below Facies L, which is interpreted as deep water marine shale (Braman 1985) (see Facies L Interpretations). Therefore, it can be inferred that deposition of Facies K took place in a marine environment that was experiencing the effects of a relative sea level rise. The trace fossil assemblage supports accumulation of sediment in upper to lower offshore settings associated with continued deepening (Pemberton and MacEachern 1995). Facies K may be the result of a pause in, or a very slow rate of, transgression, which subsequently progressed rapidly, ceasing deposition of this facies, and allowing for suitable conditions for the later deposition of Facies L.

Facies L: Black, fissile shale

Lithology and Sedimentary Features: A fissile, finely-bedded, black shale characterizes this facies (Figure 2.15 A). Due to the recessive nature of the sediment, this facies is only observed locally. Where it is observed and described, no other sedimentary features are identified within it. The contact between Facies L and the sandstone of the Aklavik Formation is very sharp (Figure 2.15 B, C). This facies is most commonly observed overlying Facies I and K (Figure 2.15 C).

Ichnology: No biogenic activity was observed.

Interpretation and Discussion: Facies L was deposited in an offshore, fully marine environment, where the primary mode of deposition was from suspension fallout. This facies is part of the Husky Formation, which directly overlies the Aklavik Formation, and is not the primary focus of this study. The interpretation of this facies is based largely on previous work and the stratigraphic position of the formation within the overall shoaling upward shoreface succession interpreted for

Figure 2.15

Facies L: Black, fissile shale

A. Fissile, finely-bedded black shale characterizes Facies L. This unit is part of the overlying Husky Formation.

B. Facies L is highly recessive; when it is present, which was mostly in the eastern region of the study area, it sharply overlies the Aklavik Formation.

C. A close-up of the sharp contact between Facies I (Aklavik Formation) and Facies L (Husky Formation).

A

B

C

the Aklavik Formation. The depositional environment was interpreted by Braman (1985) to be a shallow, siliciclastic, marine shelf, which was oriented northeast-southwest, and deepened towards the north. The lack of observed burrowing is most likely a factor of poor outcrop preservation, but it may also be a reflection of other causes, such as the lack of lithologic contrast that would allow for burrows to be visible, or the presence of environmental stresses, creating a hostile living environment.

2.3 Summary

Within the study area, twelve facies were identified, comprising predominantly the Aklavik Formation, but also including small amounts of the underlying Richardson Mountains Formation and the overlying Husky Formation. These facies represent an overall coarsening upward, progradational succession, interpreted as wave-dominated deltaic and associated shoreface deposits. An apparent flooding caps the Aklavik Formation, as indicated by the transgressive deposits of Facies I and the deeper water deposits of the Husky Formation. Chapter 3 extends more detail to this interpretation.

CHAPTER THREE: DEPOSITIONAL ENVIRONMENTS AND STRATIGRAPHIC ARCHITECTURE

3.1 Introduction

The previous chapter described the sedimentology and ichnology of each of the twelve facies identified in this study, and discussed their associated interpretations. Building on these concepts, this chapter extends the interpretations to include specific depositional environments and assembles these environments into a depositional model, which is useful as a predictive tool for extrapolating into areas adjacent to the study area. This model will be illustrated in detail and compared to a modern analogue for enhanced understanding.

The relatively dense localities of examined sections allow for the application of sequence stratigraphic concepts. The identification of two systems tracts will be addressed in an oblique-to-strike oriented cross-section, which also includes one subsurface data point. The predictive power of the cross-section is improved by using sequence stratigraphy. This will be clearly demonstrated.

3.2 Depositional Environments

3.2.1 Regressive Strata

Within the study area, the facies identified for the Aklavik Formation predominantly support a depositional model consisting of a prograding, wave-dominated delta with attached shorefaces (Figure 3.1). Evidence for this is derived from the nature of the ichnology and sedimentology of the entire facies package. From many of the outcrop exposures examined, deposition primarily took place within a wave-dominated, but heavily storm-influenced, shoreface setting; only in certain localities was deltaic sedimentation recognized. Figure 3.2 shows a schematic representation of the depositional environments of the Aklavik Formation and associated strata immediately above and below. Focusing on the Aklavik Formation, deposition ranged from the upper shoreface to the lower shoreface. Facies of the underlying Richardson Mountains Formation indicate deposition in the upper and lower offshore and possibly deeper, while facies of the overlying Husky Formation indicate predominantly shelf deposition.

By definition, a wave-dominated coast occurs when wave energy overwhelms tidal energy (Heward 1981; Davis and Hayes 1984). A coarsening upward trend demarcates wave-dominated shorelines, whereas a fining upward trend distinguishes tide-dominated settings (Davis and Hayes 1984). Shore parallel sand bodies, such as longshore bars, beaches, and beach ridges, are associated with wave-dominated shorelines (i.e. the laterally extensive nature of the outcrop of the Aklavik Formation), while shore normal sand bodies develop on tidal shorefaces (Davis and Hayes 1984). These noted characteristics combined with the abundance of wave-formed sedimentary structures and the well-sorted and well-winnowed character of the sediment of the Aklavik Formation support the interpretation of a wave-dominated coastal environment.

Shoreface deposits have the highest chance of preservation where the sediment accumulation is rapid enough to cause the shoreline to prograde seaward (Clifton 1981). The shoreface succession

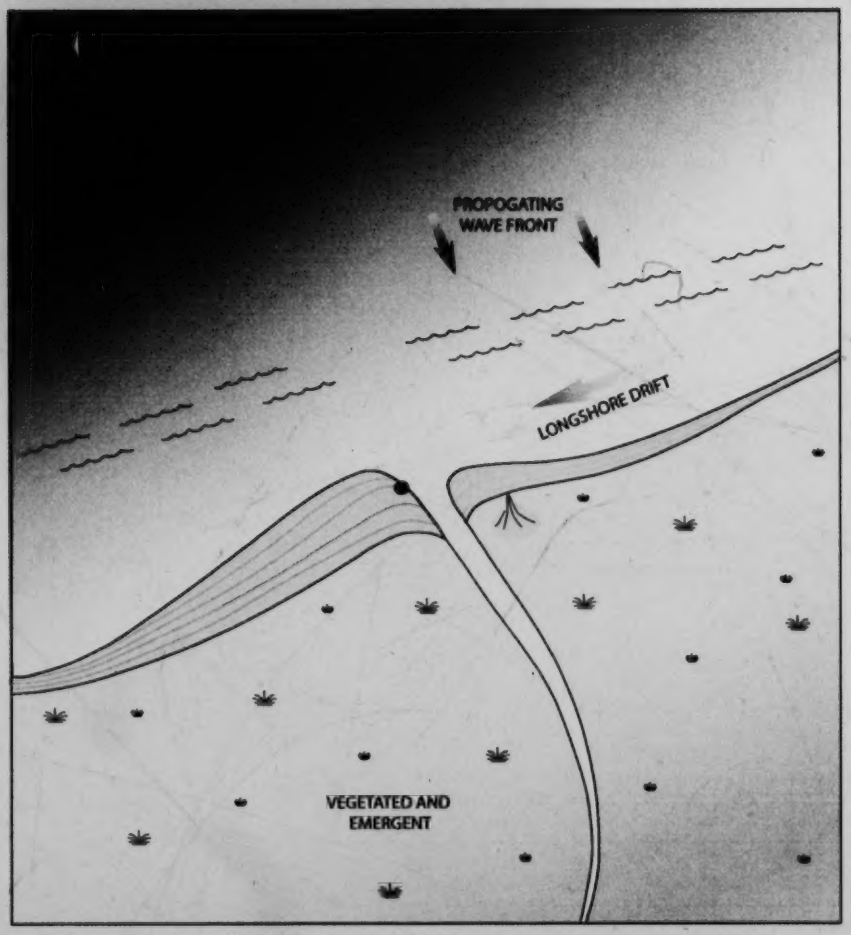


Figure 3.1 Idealized depositional model for the Aklavik Formation. The diagram is representative of the progradational facies of highstand only, specifically at the time just prior to the onset of transgression. With the shift to transgressive conditions, progradation of the Aklavik delta ceased and the environments would have changed significantly. Note the black dot represents the approximate location of the schematic litholog depicted in Figure 3.2.

of the Aklavik Formation is well preserved, as well as significantly thick, both of which support the existence of an appreciable sediment source during deposition, specifically from the input of fluvial systems. Thick shoreface deposits that appear to have been deposited rapidly are typically associated with wave-dominated deltas and their associated strandplain deposits (Curray *et al.* 1969; Coleman and Wright 1975; Heward 1981). The abundant sediment supply that is commonly related with these environments can cause rapidly prograding sheet sands, in the order of one to three kilometers in 100 years (Van Straaten 1960). The strandplains alone can extend hundreds of kilometers alongshore, especially if fed by more than one river. For example the Nayarit coast

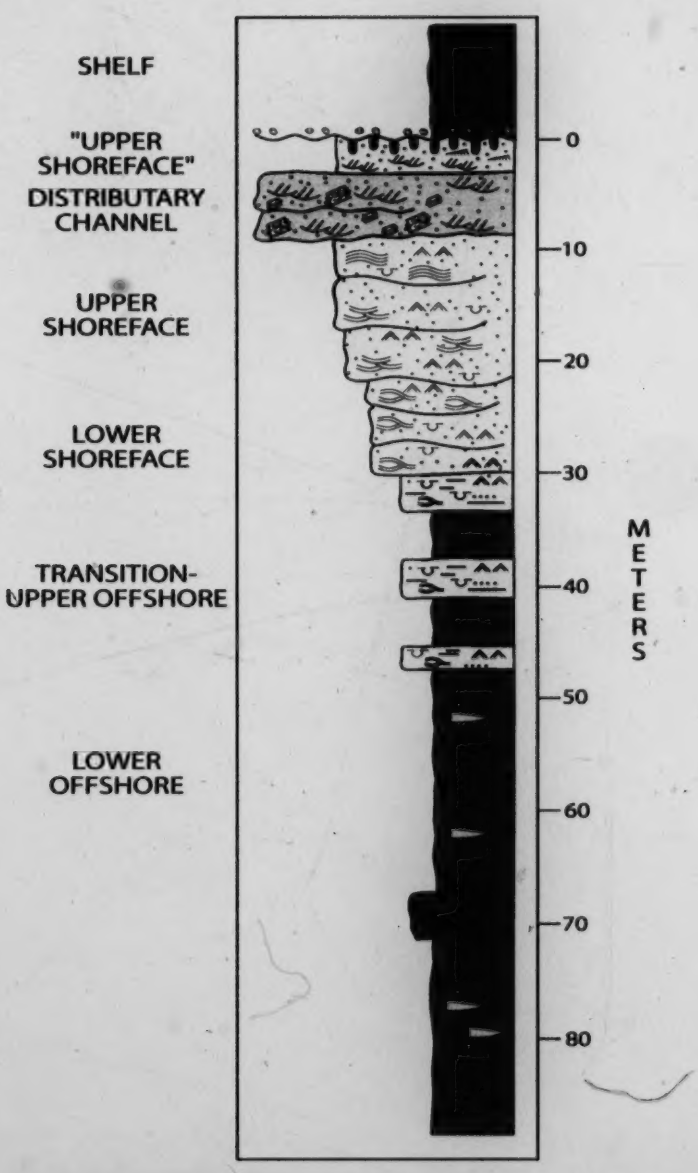


Figure 3.2 Schematic representation of a summary litholog, illustrating the facies and depositional environments of the Aklavik Formation, as well as portions of the associated formations, the underlying Richardson Mountains and the overlying Husky. The relative location of this litholog is depicted in Figure 3.1 with a black dot.

extends 225 kilometers along the west coast of Mexico (Curray and Moore 1964). Literature provides several modern examples of rapidly prograding beaches or strandplain deposits, i.e. Costa de Nayarit, Mexico (Curray and Moore 1964), the Doce River, Brazil (Dominguez and Wanless 1991), and the São Francisco River, Brazil (Coleman and Wright 1975; Coleman 1981). All of these examples are related to abundant sediment supply commonly from adjacent deltas.

Unlike river-dominated deltas where active deposition takes place in lobes immediate to the shoreline protuberance (Coleman and Prior 1982; Wright 1985), deposition in connection with wave-dominated deltas typically involves sediment reworking and transport, where it is then smeared along the coastline due to longshore drift (Coleman and Wright 1975). The result is that pro-delta deposits, which are typically very distinctive in river-dominated settings (Coleman and Prior 1982), more closely resemble wave-dominated shoreface deposits, and are therefore easily misidentified. Specific to the Aklavik Formation, the wave-dominated delta interpretation resulted from the identification of a distributary channel (Facies H) that incised into the upper shoreface deposits in the eastern region of the study area. Therefore, the coarsening upward trend that characterizes facies of the Aklavik Formation represents active deltaic sedimentation gradually infilling the basin.

The facies of the Aklavik Formation suggest proximity to a paleo-shoreline in the eastern region of the study area, with a relative deepening trend towards the west. These observations are further supported by the basin configuration and the paleogeography (see Chapter 1, section 1.7). The topographic highlands, landward of the shoreline, provided the abundant quartz-rich sediment which was transported into the basin by multiple point sources. In the study area, only a single point source was identified, but it is likely that more existed. Earlier observations by previous workers, specifically of the sedimentary characteristics of the Aklavik sandstone farther to the south and north of the study area, provide the basis for this idea (Poulton *et al.* 1982).

Specific to the study region, sediment was transported via a single fluvial channel system, and entered the basin by means of a wave-dominated delta. Fluvial or non-marine facies were not observed, but because of the necessary large bed load and the overall lack of mud in the distributary channel deposits, a confined braided channel system is more likely to have been the fluvial style rather than a meandering one (Hamblin and Walker 1979).

At the time of Aklavik deposition, the basin was exposed towards the north and northwest to the open ocean, and was not sheltered from storms or large wave development. The result was that sand was reworked almost continuously by storm waves, therefore thick deposits of storm generated bedforms are the typical facies of the Aklavik Formation. The impact of storms is discussed in greater detail in section 3.2.3. Sediment was carried along the coastline by the means of longshore currents, creating thick strandplain deposits. These strandplain deposits are represented by the shoreface succession, common in the study area and to all of the Aklavik Formation.

Accurately recording longshore drift from the rock record can be extremely challenging, because of the large number of measurements required for the study to even be valid, as well as the typically well-exposed outcrop necessary. For the purpose of the depositional model of the Aklavik

Formation, the direction of longshore drift was inferred from the Coriolis Effect. Longshore drift in the open ocean is greatly controlled by this phenomenon (Komar 1976a; Davis 1977; Brown *et al.* 1999), which causes ocean currents to circulate clockwise in the northern hemisphere. As a result, it is speculated that sediments debouched from any deltaic source during Aklavik time would have been effectively transported by longshore drift, which is best developed and most efficient on coasts that have gently sloping beaches and straight shorelines (Brown *et al.* 1999).

Sediments of the Aklavik Formation were depoisited along a broad, shallow shoreface, classified as a dissipative beach (Wright *et al.* 1979). Beach profiles of this type are typical in high energy, relatively finer-grained settings, where storms produce the broad, dissipative profiles through erosion, and fair-weather waves heal the profile by the means of transporting sediment back to the shoreface (Wright *et al.* 1979). If fair-weather time is significant enough, the profile can become steep by swash accretion and landward migration of nearshore bars (Galloway and Hobday 1996). Barrier bars are commonly associated with wave-dominated coasts, but are lacking within the shoreface deposits in the study area. Their lack of preservation is the result of high energy and frequent storms, which continually reworked much of the shoreface. These storm surges may have cut through any form of bar development, preventing their build-up, and remobilized the sediment, transporting it in an offshore direction. The lack of sizeable barriers would have also prevented the intensity of the storm waves from dissipating prior to reaching the shoreface; as a result, the shoreline was greatly affected during storm events.

In the vicinity of the delta mouth, the sediments are characterized by lower levels of bioturbation than are typical across the study area, as well as higher occurrences of detrital organic matter, commonly in the form of preserved wood lag impressions. Moving west in the study area, where facies are distal from the point source, the sediments are characterized by thick, amalgamated storm deposits, indicative of frequent storms on a high energy, wave-dominated coast. These distal facies are better described as shoreface, rather than deltaic deposits because of the significant influence of waves, which were large enough to rework most of the debouched sediments and overprint deltaic sedimentation, aside from deposits immediate to the river mouth. As previously mentioned, this over-printing by wave energy results in the frequent misidentification of deltaic deposits, specifically the delta front deposits that, in a wave-dominated setting, more closely resemble shoreface deposits. A comparison between deltaic and shoreface deposits is schematically illustrated in Figure 3.3. The dominant wave influence would have also overprinted any tidal activity that may have been present during deposition of the Aklavik Formation.

3.2.2 Transgressive Strata

The majority of facies of the Aklavik Formation support regressive deposition. However, these deposits are capped by four facies, Facies I, J, K, and L, which are interpreted as transgressive deposits. The shift from regression to transgression resulted in the termination of progradation of the Aklavik delta, and the ensuing submergence of the coastline. Within the upper strata of the Aklavik Formation, data is limited, and general interpretations are therefore made with speculation.

Transgression of the Aklavik delta and associated coastline caused the reactivation of the shoreface, and erosion of much of the upper regressive deposits (i.e. the foreshore and backshore).

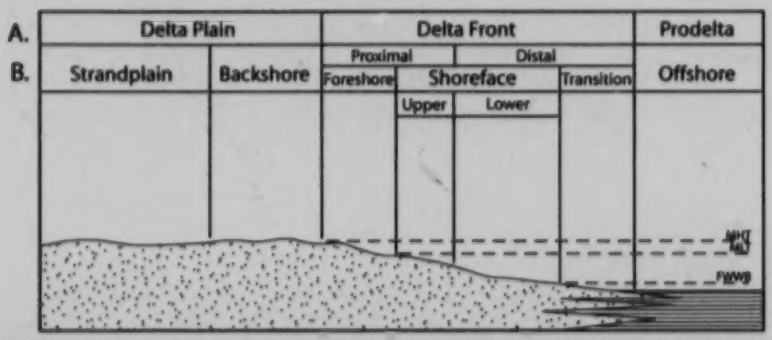


Figure 3.3 Diagram comparing the associated depositional environments and their lateral distribution along the seaward margin of a wave-dominated deltaic depositional system (A) and a strandplain depositional system (B). The importance of this diagram is to illustrate the similarity, and therefore potential ease of misidentification, of delta front deposits with shoreface deposits (modified from Moslow and Pemberton 1988). MHT = mean high tide; MLT = mean low tide; FWWB = fair-weather wave base.

Transgression also contributed to erosion of most transgressive deposits due to submergence and reworking by fair-weather currents. It is highly likely that as a consequence of transgression and the ensuing erosion of any type of beach berm, storm influence at the end of Aklavik time would have been greatly dissipated, resulting in greater preservation of fair-weather processes (Saunders pers. comm. 2003). The decreased influence of storm waves, and possibly fair-weather waves as well, would have allowed for tidal effects to be more apparent during deposition. Therefore the interaction of both wave and tidal currents can be anticipated within these transgressive deposits. It is speculated that the flooding of beach ridges in the strandplain environment created a barrier island system. The main piece of evidence for a barrier island system is the interpreted preservation of a possible tidal inlet, situated between two barrier islands.

Transgression at the end of the Aklavik Formation was probably more of a punctuated, rather than continuous, event. As a result, deposition followed by erosion from transgressing waves was typical. Therefore, the strata characterizing this geologic time are not fully preserved, and present an exceptionally limited picture of the depositional environment. With each ensuing flooding event, erosion of the barrier island system resulted, and in localized areas, a lag consisting of sediments from these eroded environments was deposited. Ultimately, as the transgressive event became more significant, deepening produced extensive landward backstepping of facies, allowing for deposition of shelf sediments in the vicinity of the previously existing Aklavik shoreline.

3.2.3 Intense Winter Storms

Numerous authors have discussed and summarized the sedimentological affects of intense storms, such as hurricanes and winter storms (see Hayes 1967; Marsaglia and Klein 1983; Duke 1985; Morton 1988; Saunders *et al.* 1994). Great interest is commonly given to storms because of their ability to accomplish in hours the same sedimentological work that normally takes years (Morton 1988). Many of the facies identified in the study area of the Aklavik Formation indicate the presence of storms during sedimentation. Due to this significant influence, it becomes

necessary to discuss in detail the effects of storms and the conditions required for their formation. Addressing this will widen the understanding of the paleogeography and paleoclimate during the Late Jurassic.

The length of affected coastline is the best measure of the geological scale of a storm (Morton 1988). Taking this into consideration, it can be suggested that the most violent storms may affect an entire depositional basin. For example, the Gulf of Alaska has an exceptionally stormy coastline, and extreme atmospheric and oceanic conditions can cause very large storms to occur roughly every 100 years (Danielsen *et al.* 1957; *in* Morton 1988). In the winter of 1952, one of these storms hit the Gulf, affecting 1300 kilometers of coastline, and had a maximum wave height of 15 meters and a peak wind velocity of 31 meters/second (Danielsen *et al.* 1957; *in* Morton 1988). Storms of this size are typically rare events for any given nearshore region, but less intense storms can occur more frequently, and are able to produce much of the storm-related features preserved in the rock record. Storms of this intense magnitude were probably not the norm during deposition of the Aklavik Formation, but presumably they did occur.

During the Mesozoic, which was a non-glacial time, warmer conditions than the climate of today prevailed (Frakes 1979). As a result, Duke (1985) suggested a broadened hurricane distribution belt existed during this time, allowing for hurricanes to occur more frequently at higher latitudes. Outside this hurricane belt, intense cyclone type storms occur; the storms that effect latitudes north of this belt are termed intense winter storms (Duke 1985). Intense winter storms may originate over continents or oceans, and form along fronts between cold and warm air masses (Strahler and Strahler 1989). Even with the relatively warm conditions, extensive polar land areas were snow-covered in the winter during parts of the Mesozoic (Frakes 1979), suggesting that it was possible for cold polar air masses to form. The belt of intense winter storms during the Mesozoic was within similar paleolatitudes to that of modern occurrences (Duke 1985). However, the significantly warmer climate during this time would have allowed for the season of ice-free ocean to be extended, thus providing a greater opportunity for storm influence across a larger area (Morton 1988).

Even with the broadened hurricane belt during the Mesozoic, the paleogeography of the Brooks-Mackenzie Basin, as well as the position of the North American Plate, imply that intense winter storms and associated smaller storms were the primary weather system that contributed to the formation of much of the storm deposits during the Aklavik Formation. Storm beds are pervasive across the entire study area, but specific to the western region, relatively uninterrupted successions of these deposits are typical. This record of amalgamation is the product of intense, high frequency winter storms that were possibly occurring on an annual basis. Saunders *et al.* (1994) noted similar observations and interpretations, in relation to progradation of the Cretaceous Cadotte Member. This interpretation is further substantiated by similar evidence of paleogeography and paleolatitude and occurrence of winter storms by Marsaglia and Klein (1983) and Duke (1985).

3.2.4 Comparison with Previous Work

Overall, the general interpretations of the Aklavik Formation described in this study agree with previous published work, specifically Poulton *et al.* (1982). Poulton *et al.* (1982) recognized the Aklavik Formation as a high-energy marine shelf sandstone, but noted that it could not be

described as typically deltaic. The confirmation of deltaic influence within this study stems from the identification of Facies H, a distributary channel fill, which incised into the upper shoreface, as well as the significant sediment supply available during Aklavik deposition. The abundance of wave-dominated features that characterize the Aklavik Formation assisted with the interpretation of a wave-dominated deltaic setting, manifested by parallel shoreface sand bodies. The interpreted environment, as already outlined in this chapter, does not consist of deposits that can be described as "typically deltaic", as stated, unknowingly, by Poulton *et al.* (1982).

3.3 Shoreface Terminology

With the identification of the Aklavik Formation as being related to shoreface deposits, it becomes essential to clarify on the terminology associated with this depositional model. In the literature, numerous terms have been used to describe similar processes, especially when comparing shoreface deposits of modern and ancient examples (e.g. Campbell 1971; Clifton *et al.* 1971; Hamblin and Walker 1979; Clifton 1981). Modern examples typically define the shoreface in terms of coastal processes (e.g. surf zone; Clifton *et al.* 1971) where as ancient examples are commonly described in terms of tidal zones (e.g. mean high water; Pemberton *et al.* 1992) or wave base zones (e.g. fair-weather wave base; Walker and Plint 1992). The shoreface model described by Pemberton and MacEachern (1995), and based on Cretaceous strata of the Western Interior Seaway of North America, is adapted in this study, and presented in Figure 3.4. Because of the various methods for defining the shoreface, it is necessary to outline and define the terminology that is associated with this model and the shoreface deposits of the Aklavik Formation.

When describing a shoreface environment, it is essential to recognize that the boundaries are the result of dynamic processes. In relation to this specific study on the Aklavik Formation, the boundaries of fair-weather and storm wave base in particular were considered dynamic, and therefore not thought of as static limits that did not fluctuate due to seasonal variations. Figure 3.5 represents a schematic profile through an idealized shoreface complex, and depicts the terminology that is used for this study. This diagram summarizes the divisions of the shoreface, including the different facies that make up each division, as well as incorporates a schematic litholog for illustrating the shoreface deposits specific to the Aklavik Formation.

3.3.1 The Backshore

The backshore is the region that is landward of mean high tide. Consequently it is always exposed and is considered the supratidal zone (Reineck and Singh 1980). This zone is nearly horizontal to gently dipping in a landward direction (Davis 1978). Deposits such as washover fans, beach ridges, and storm berms are common (Reineck and Singh 1980), as well as the presence of vegetation (Komar 1976b). The backshore is separated from the foreshore by a topographic high point called the berm or berm crest (Davis 1978). Deposits of this nature were not identified in the study area in association with the Aklavik Formation, but speculation is made on the probable features that may have characterized this formation in section 3.5.

3.3.2 The Foreshore

The foreshore is the zone between high and low tide, and is considered the intertidal zone (Reineck and Singh 1980; Pemberton *et al.* 1992). An abrupt increase in slope gradient demarcates the

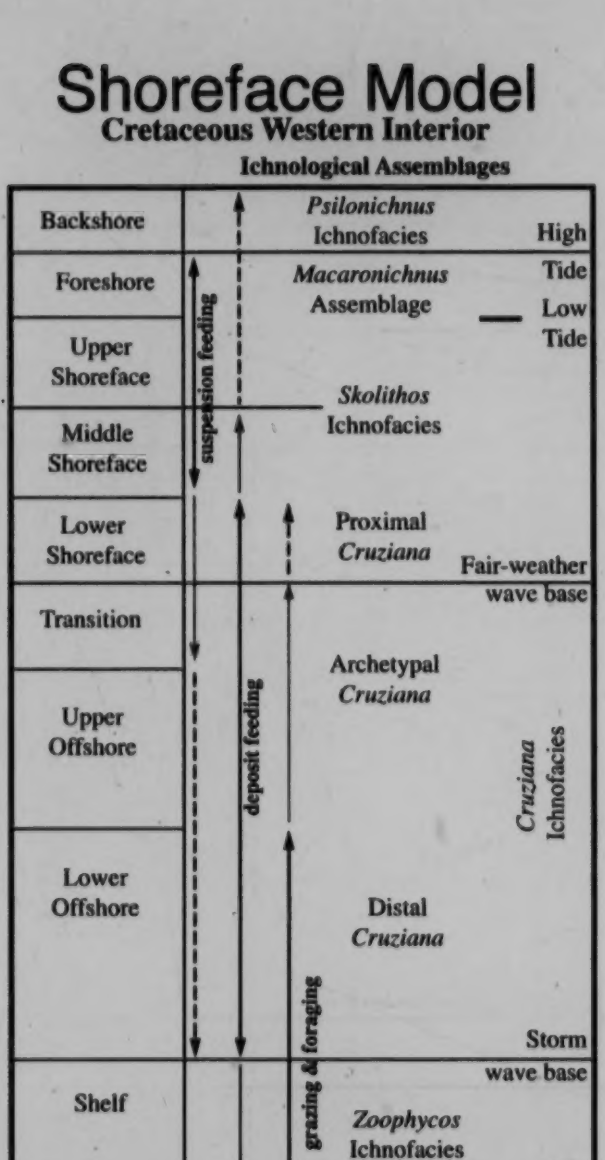
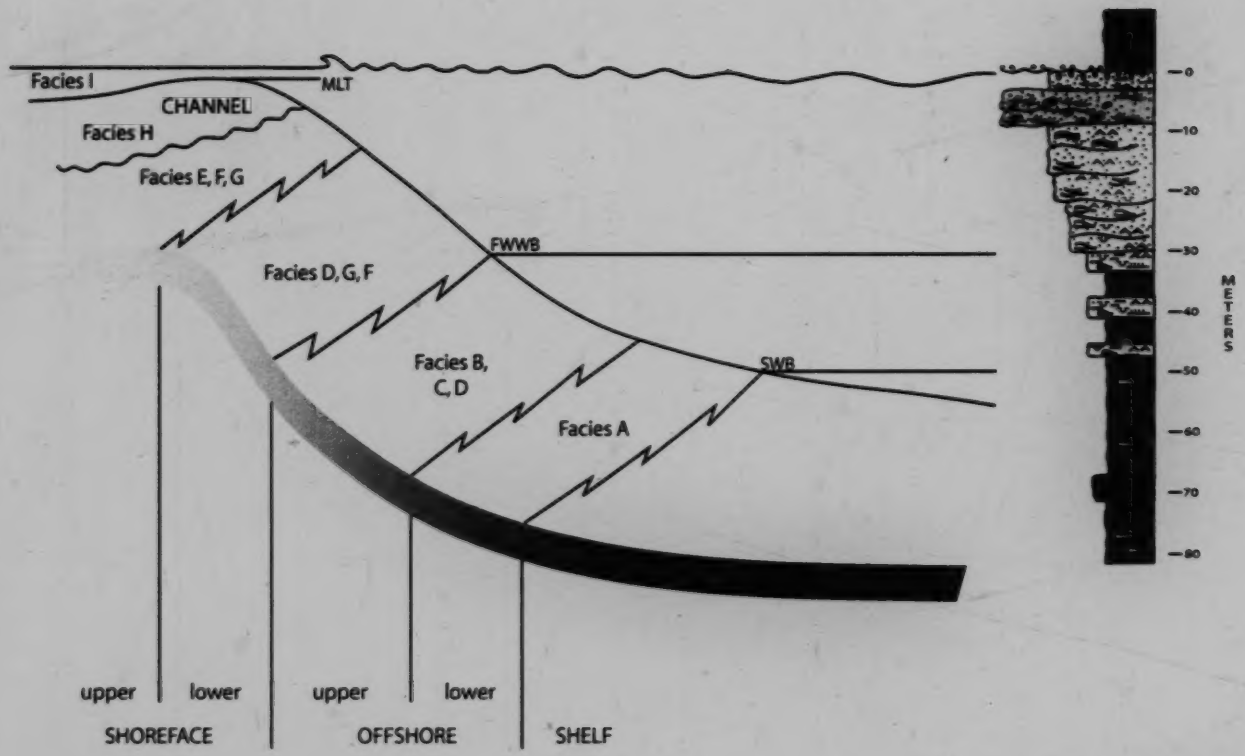


Figure 3.4 Idealized shoreface model used in this study. The distribution of ichnological assemblages is illustrated, however their occurrences alone do not define the divisions of the shoreface. This model is based on data from the Cretaceous strata of the Western Interior Seaway of North America (modified from Pemberton and MacEachern 1995).

Figure 3.5

Schematic profile through an idealized shoreface complex, depicting the terminology that is used in this study. The divisions of the shoreface are summarized, with the different facies specific to the Aklavik Formation included. The schematic litholog from Figure 3.2 is also included. MLT = mean low tide; FWWB = fair-weather wave base; SWB = storm wave base.


Facies I
MLT
CHANNEL
Facies H
Facies E, F, G
FWWB
Facies D, G, F
Facies B,
C, D
SWB
Facies A
upper
lower
upper
lower
SHOREFACE
OFFSHORE
SHELF
0
10
20
30
40
50
60
70
80
METERS

foreshore from the backshore (Davis 1978). The slope of this zone depends on the composition and coastal processes acting upon it. Both swash and surf zone processes are present in the foreshore, but the former is the more dominant of the two (Clifton *et al.* 1971). The product of this is planar beach laminations, which characterize the foreshore (Clifton 1969). The foreshore is also referred to as the beach or beach face (Davis 1978; Walker and Plint 1992; Galloway and Hobday 1996), and is typically marked by a concentration in coarse-grained material (Davis 1978). Within the study area, foreshore deposits were not preserved, presumably reflecting the effects of erosion in association with transgression, as previously mentioned in Chapter 2, Facies J Interpretations.

3.3.3 The Shoreface

The classification of the shoreface is the most variable in the literature, but is considered to be perpetually submerged. The upper limit is agreed to be the low tide mark (Davis 1978; Walker and Plint 1992), while the lower limit has been defined both as the storm wave base (Reineck and Singh 1980) and as the fair-weather wave base (Walker and Plint 1992; Pemberton and MacEachern 1995). For the purpose of this study, the lower limit is defined as the fair-weather wave base. Walker and Plint (1992) state that the fair-weather wave base can range between a water depth of five to fifteen meters. The shoreface is characterized by day-to-day sand transport representing fair-weather conditions, but can also be punctuated by the effects of storms. In terms of coastal processes, the surf zone, which overlaps with the lower part of the foreshore, is active in the upper portion of the shoreface (Clifton *et al.* 1971). In the lower portion of the shoreface, waves initially touch the sediment-water interface (Davis 1978; Reineck and Singh 1980). This zone is termed the breaker zone by Clifton *et al.* (1971) and can extend across the entire shoreface.

The shoreface is commonly divided into at least two subdivisions, the lower and upper. Many authors identify a middle shoreface (Walker and Plint 1992; Pemberton and MacEachern 1995). Pemberton and MacEachern (1995) place emphasis on changes in ichnological assemblages in order to define the middle shoreface. For the purpose of this study, only the lower and upper shoreface divisions were identified; the trace fossils within the Aklavik Formation do not occur regularly enough to be able to recognize a middle shoreface.

Within the upper shoreface, both longshore and rip currents are active. Longshore currents transport water and sediment parallel to the shoreline, and rip currents transport water and sediment offshore (Komar 1976). The development of longshore bars also characterizes the upper shoreface (Davis 1978). These bars generally extend parallel to the shoreline and are continuous, sometimes for many kilometers. Low areas in these bars are created by rip currents and are termed rip channels (Davis 1978). During large storms, the bars are planed off; as the storm recedes, they are rebuilt. Longshore bars are typically associated with high-energy coasts. It is presumable that their lack of preservation in the Aklavik Formation reflects the high frequency of storms during this time.

3.3.4 The Offshore

Reineck and Singh (1980) and Pemberton and MacEachern (1995) identify a transition zone that can be present between deposits of the shoreface and offshore. Where this transition zone is not present, shoreface sand grades immediately into offshore sediments (Reineck and Singh 1980). This zone is generally in a water depth between 8 and 30 meters (Reineck and Singh 1980) and is

commonly characterized by inter-bedded shoreface sand and offshore mud deposits. The transition zone is coarser grained than the offshore, but finer grained than the shoreface, and typically shows a high diversity and density of trace fossils (Pemberton *et al.* 2002). Storm currents are responsible for the transportation of sand into this zone (Reineck and Singh 1980). This zone is not identified in the Aklavik Formation within the study area.

When the transition zone is not present, the fair-weather wave base marks the upper limit of the offshore zone. This frequently corresponds to where sediments become more mud-dominant, relative to the sand-dominant shoreface deposits (Walker and Plint 1992). However, it is important to note that the transition from sand to mud alone does not always define the boundary between shoreface and offshore deposits (Clifton in press). The presence and proportions of sand, silt, and mud are not necessarily controlled by the shoreface morphology (Clifton in press), but are more dependent on the sediment available and the wave-energy regime of the system (Galloway and Hobday 1996). The offshore can be subdivided into upper and lower zones. The division between these two is highly arbitrary, but is generally based on the sand content (i.e. higher amount in the upper versus lower offshore) and ichnological assemblages (Pemberton and MacEachern 1995; Pemberton *et al.* 2002). The lower limit of the offshore zone is defined as the storm wave base (Walker and Plint 1992; Pemberton and MacEachern 1995). Below this boundary, the offshore passes into shelf deposits, where sedimentation is purely from suspension fall-out.

3.4 Environmental Significance of Trace Fossils

Trace fossils, and their associated organisms, are highly responsive to ecological changes in their depositional environment; even subtle fluctuations can have dramatic effects to a burrowing benthic community (Pemberton *et al.* 1992; Pemberton *et al.* 2002). Water turbidity, water salinity, fluctuating sedimentation rates, storm energy, or a combination of these, are all typical ecological stresses that affect organisms. In the Aklavik Formation, identified trace fossils (Table 3.1) represent both the higher energy *Skolithos* ichnofacies and the lower energy *Cruziana* ichnofacies, with all of the traces indicative of relatively high-energy settings typical of shallow water marine environments. Collectively, the physical and biogenic structures suggest deposition within a wave-dominated deltaic and shoreface environment. The characteristics of each ichnofacies identified in the Aklavik Formation are outlined in Table 2.2.

3.4.1 Opportunistic Species

Opportunistic species represent organisms that are not resource limited and are able to flourish in unstable, physically controlled environments (Levinton 1970; Grassle and Grassle 1974). They are characterized by an r-strategy in population dynamics, where rapid growth (r) is emphasized. This is opposite to equilibrium species, where a k-strategy is utilized, emphasizing the carrying capacity of the environment (k) (Boesch and Rosenberg 1981; Boyce 1984). R-strategy organisms focus on reproduction, and short generation span is the most efficient mechanism for doing this (Boesch and Rosenberg 1981). The results are shorter life spans for opportunistic species, with earlier rates of sexual maturation (Grassle and Grassle 1974; Rees *et al.* 1977). The characteristics of these two species types are summarized in Table 3.2.

Ichnofossil	Ethology	Trophic Group	Possible Tracemaker
Arenicolites	domichnia	suspension feeder	Annelid or other worm-like phyla
Chondrites	fodinichnia	deposit feeder	Nematode; sipunculid (?) or polychaete worm
Cylindrichnus	domichnia	suspension feeder	Polychaete or other worm
Diplocraterion	domichnia	suspension feeder	Amphipod crustaceans; polychaete worm (?)
Helminthopsis	pascichnia	grazing trace	Annelid, polychaete or other worm-like phyla
Ophiomorpha	domichnia/ fodinichnia	suspension feeder	Crustacean (thalassinid decapod)
Palaeophycus	domichnia/ repichnia	carnivore; suspension feeder (?)	Annelid or polychaete worm
Planolites	fodinichnia	deposit feeder	Annelid or other worm-like phyla
Polykladichnus	domichnia	suspension feeder	Annelid or other worm-like phyla
Rosselia	fodinichnia/ domichnia	deposit feeder	Annelid or other worm-like phyla
Skolithos	domichnia	suspension/deposit feeder; carnivore	Annelid, phoronid or other worm-like phyla
Teichichnus	fodinichnia/ domichnia	deposit feeder	Annelid, phoronid or other worm-like phyla

Table 3.1 Identified trace fossils from the Aklavik Formation in the study area. Their ethological classification, trophic group, and possible trace maker are also suggested for each trace.

r-Selected (opportunistic)	K-selected (equilibrium)
1. responds rapidly to open niche	1. slow to colonize
2. lacks equilibrium population size	2. reach population size equilibrium
3. density-independent mortality	3. density-dependent mortality
4. relatively poor competition ability	4. excellent competitors
5. high dispersal ability	
6. efficient reproductive system	

Table 3.2 Characteristics of r-selected and K-selected poplulations (taken from Pemberton and MacEachern 1997, modified after Pemberton *et al.* 1992).

Opportunistic species are able to rapidly colonize open niches because of their trophic generalist behavior and their ability to tolerate a wide range of environmental factors (Levinton 1970). Populations of these species are generally unstable and may become extinct very quickly (Levinton 1970). Suspension-feeding or surface deposit-feeding behaviours are most commonly adopted by these species (Pemberton *et al.* 1992; Pemberton and MacEachern 1997). However these organisms have a great capacity of varying their feeding habits depending on food availability (Cadée 1984). Along with conditions that are unsuitable for most organisms, opportunistic species further inhibit the possibility of competitors from colonizing the same substrate by living in dense communities (Rhoads *et al.* 1978). The recognition of explosive opportunists in the rock record, therefore, is a viable means for identifying communities that were primarily controlled by the physical, rather than the biotic, environment (Levinton 1970).

Criteria for recognizing opportunistic trace fossil assemblages are summarized below (Pemberton and Frey 1984; Pemberton and MacEachern 1997; and references therein):

1. Limited areal distribution
2. Occurring in continuous, thin horizons
3. Abundant in several otherwise distinct faunal assemblages
4. Present in high densities in facies with which it is not typically associated
5. Numerical domination of one species within the fossil assemblage

Generally, the mixed *Skolithos-Cruziana* ichnofacies assemblage commonly identified in the Aklavik Formation displays all of these characteristics, in variable degrees across the study area (see Chapter 2, Facies A, C, D, E, F, I ichnology descriptions).

3.4.2 Deltaic Deposition

Deltaic environments are generally very harsh settings for burrowing organisms. Ecological stresses such as enhanced rates of sedimentation, increased water turbidity, and reduced or fluctuating salinity levels are imminent. Decreased levels of bioturbation can result from a single ecological stress being applied to the environment; the coupling of more than one stress can

be devastating to the benthic community, resulting in an absence of burrows (MacEachern and Pemberton 1992; Pemberton *et al.* 2002).

Low diversity of trace fossil assemblages can be used to identify deltaic deposits. Moslow and Pemberton (1988) used this method, and attributed the reduced number of organisms to the harsh ecological conditions related to increased water turbidity and fluctuating rates of deposition. It is possible that these factors, along with fluctuating salinity (specifically in relation to settings proximal to the mouth of the river) and water energy (attributed to storm disturbances), contributed towards ecological conditions that were ultimately too stressful for the permanent development of a community of diverse, densely packed organisms during much of Aklavik time. The identification of sporadic trace fossil assemblages in the facies of the Aklavik Formation reflects the unstable nature of the ecological conditions.

In a study of a wave-dominated deltaic allomember of the Cretaceous Dunvegan Formation of the Western Canadian Sedimentary Basin by Gingras *et al.* (1998), the key stress upon the resident community in the subaqueous delta front was determined to be the length of time available for colonization by benthic organisms. The preservation potential of an equilibrium suite of trace fossils reflecting fair-weather conditions was found to be very similar to assemblages described from normal marine, lower shoreface environments of the Cretaceous Western Interior Seaway (see MacEachern and Pemberton 1992). Based upon this similarity, extrinsic stresses such as salinity fluctuations, anomalously high sedimentation rates, temperature fluctuations, or high water turbidity were ruled out.

In contrast to the study by Gingras *et al.* (1998), specific stresses during Aklavik deposition are very challenging to pinpoint. This is due to the poor preservation potential of an equilibrium suite of ichnofossils, especially in the delta front (i.e. shoreface), which continually experienced erosion by persistent storms. The dominant physical sedimentary structures imply that overall, the most effective stress on the marine community was frequent disturbances due to storms, which, as mentioned by Gingras *et al.* (1998), would have affected the length of time available for colonization. This is supported not only by the dominance of storm generated bedforms in the Aklavik Formation, but also by the appearance of localized trace fossil assemblages that are characterized as newly developed, opportunistic suites. However, due to the lack of preservation of an equilibrium community, the presence of stresses such as salinity changes, high sedimentation rates, or high water turbidity cannot be considered irrelevant.

The high energy, wave-dominated deltaic and coastal depositional environments of the Aklavik Formation provided a relatively unstable setting for organisms to live in. Fluctuating water energy levels, sedimentation rates, salinity, and water turbidity all contributed towards a challenging environment for burrowing organisms. Out of all of these possible physiological stresses, fluctuating water energy resulting in scouring, attributed to storm generated currents, imparted the greatest effects upon the benthic communities during deposition of the Aklavik Formation. Only the most adaptable species could have successfully established themselves during this time. The result was localized occurrences of burrowing communities, generally low in diversity and density, relative to more typical (lower energy) nearshore marine environments (see Howard and Frey 1984;

Frey and Howard 1990; Dam 1990; MacEachern and Pemberton 1992; Pemberton *et al.* 1992; and Raychaudhuri *et al.* 1992 for descriptions of lower energy shorefaces).

3.4.3 Storm Deposition

Storm deposition is believed to greatly influence trace fossil distributions in the Aklavik Formation. The largest stresses resulting from storms include episodic sedimentation rates and fluctuating water energy. Storm influence is represented in many of the facies of the Aklavik Formation, for example the pervasive occurrence of HCS and SCS bedforms, and the common observation of the finer grained facies showing rare to abundant inter-beds of storm induced sandstone. The local fluctuations in energy level and sedimentation rate would have been a change from the typical conditions, therefore exerting a large influence on the distribution of the burrowing organisms.

In parts of the Aklavik Formation, a somewhat mixed assemblage of traces from both the *Cruziana* and *Skolithos* ichnofacies is observed within a single depositional cycle. Specific to the Aklavik Formation, elements of the *Cruziana* ichnofacies are dominantly sub-vertical and associated with sandy substrates, suggesting that the assemblage is atypical of the archetypal ichnofacies (see Table 2.2), and is better described as proximal *Cruziana*. The presence of the two ichnofacies reflects varying behavioural responses of the organisms colonizing two successive, individually unique settings (Pemberton and MacEachern 1997).

Traces of the *Cruziana* ichnofacies are interpreted as the resident fauna, representing the presence of a stable benthic community with low physiochemical stress (Pemberton and Frey 1984; Pemberton and MacEachern 1997). The trace fossils of the *Skolithos* ichnofacies associated with storm deposits represent a community of opportunistic organisms, flourishing in an unstable, high-stress, physically controlled environment (Pemberton and Frey 1984; Pemberton and MacEachern 1997). These organisms rapidly colonized the surface of the storm sand due to the lack of competition, a situation that is very different from low stress marine environments, where equilibrium populations are typical (Vossler and Pemberton 1988; Pemberton and MacEachern 1997). The intermixing of components from both the *Skolithos* and the *Cruziana* ichnofacies indicates that following deposition of the storm bed and subsequent colonization, more stable conditions eventually returned, allowing for the resident faunas to return to the area.

In the study previously mentioned by Gingras *et al.* (1998), a paucity of burrows was noted in the facies of the wave-dominated deltaic setting, reflecting a preservational bias of traces. Due to the lack of equilibrium trace fossil suites associated with the deposits of the proximal delta front, it was concluded from the robust and moderately diverse appearance of the *Skolithos* ichnofacies elements that the ecological conditions were not overly stressful. Consequently, the trace fossil suite was not classified as a stressed *Skolithos* assemblage, but was regarded as a "healthy", though incompletely preserved, *Skolithos* ichnofacies association.

Like the trace fossil suites identified by Gingras *et al.* (1998) in the wave-dominated allomember, the trace fossil suite of Facies D can also be considered a "healthy" but incompletely preserved *Skolithos* assemblage. Traces of this facies reflect colonization by opportunistic species that were able to adapt to post-storm conditions. Development of an equilibrium community most likely ensued with waning storm conditions, but was removed due to erosion from subsequent storm

currents. Therefore, the greatest stress imposed on the organisms was the persistent disturbance by storms, which typically resulted in the full removal of any accumulated and colonized fair-weather deposits.

3.4.4 Preservation Potential of Storm Deposits

Dissipation time, as defined by Pemberton and MacEachern (1997) corresponds to the time required to destroy an event bed biogenically, and the type of ichnological assemblage associated with the deposit directly effects this time. Generally, trace makers of the *Cruziana* ichnofacies, characterized by horizontal to sub-vertical feeding traces, are able to cause more disruption of the sediment relative to the trace makers of the *Skolithos* ichnofacies, characterized by vertical shafts (Pemberton and MacEachern 1997). Vertical dwelling and suspension feeding structures are able to penetrate deeply into the substrate, but typically display minimal volumetric modification of the bed (Pemberton and MacEachern 1997). Therefore, traces of the *Skolithos* ichnofacies are not able to homogenize the sediment to the same degree that trace makers of the *Cruziana* ichnofacies are capable of (Pemberton and Frey 1984). Consequently, the amount of sediment modification by organisms in the Aklavik Formation was limited to begin with simply due to the behaviour of the trace makers, which resulted predominantly in vertical shafts.

It is important to note that biogenic reworking of the sediment rarely begins immediately following a storm event (Pemberton and MacEachern 1997). Typically, deposition of a tempestite (i.e. a storm bed) succeeds a disturbance that displaces or destroys most of the resident community, resulting in a deposit that may be unpopulated for a considerable amount of time (Pemberton and MacEachern 1997). Once recolonization of an event bed is initiated, even more time is required before the burrowing community reaches the density that it was prior to the disturbance (Sousa 1984). Therefore a significant amount of time is required during fair-weather conditions to allow for the modification of storm deposits.

High latitude settings, such as that of the Aklavik Formation, demonstrate cyclic variations in storm activity, and are characterized by a winter and summer storm season (Owens 1977). During the winter season, storms are both frequent and of high magnitude, with the summer season represented by less frequent storms of lower intensity (Owens 1977). Due to these cycles, storm deposits accumulate quickly during the winter season, and show little to no biogenic reworking due to the limited fair-weather time available. Biogenic reworking is more favorable during the summer season, when fair-weather conditions are typically longer. However, burrows that are created are largely restricted to the tops of storm beds (Pemberton and MacEachern 1997). Evidence for these conditions is abundant in the Aklavik Formation, where most storm deposits are amalgamated or show very little biogenic reworking that is restricted to the upper portion of the sandstone beds.

Along with the interpretation that amalgamated storm beds in the Aklavik Formation are generally the products of high frequency winter storm, these deposits are also interpreted to be associated with shallower water settings, where storm currents are able to physically rework the sediment regardless of the magnitude of the disturbance. With persistent storms, minimal accumulations of fair-weather sediments are able to collect on the tops of tempestites, with limited time available for

biogenic modification of the sediment (Pemberton and MacEachern 1997). The result is a higher preservation potential of the storm deposits.

Storm deposits have regularly been identified in the wave-dominated shoreface intervals in the Western Interior Seaway of North America (Pemberton and Frey 1984; Saunders and Pemberton 1986; Vossler and Pemberton 1988; Pemberton *et al.* 1992; Raychaudhuri *et al.* 1992). Typical to many of these deposits are successions of laminated to burrowed sediments, described as "lam-scram" bedding, with both storm (lam) and fair-weather (scram) conditions represented (Pemberton *et al.* 1992). Storm deposits of the Aklavik Formation, however, have limited examples of this style of bedding because of the low preservation potential of the fair-weather deposits, as a result of storm scouring. The shallow water position on the shoreface and the frequency and intensity of storms all contribute, collectively or individually, to the amalgamation of laminated storm beds, where the fair-weather deposits are missing due to erosion from the successive storm (Figure 3.6). As a result, any traces that are preserved are typically representative of the opportunistic organisms that initially colonized the substrate. Presumably, with the return to more stable conditions, a community of diverse benthic forms inhabited the substrate, creating numerous traces belonging to the *Cruziana* ichnofacies. These fair-weather deposits are rarely preserved in the rocks of the Aklavik Formation, resulting in a biased representation of trace fossils, dominated by vertical to sub-vertical forms of the *Skolithos* and proximal *Cruziana* ichnofacies. Figure 3.6 illustrates the

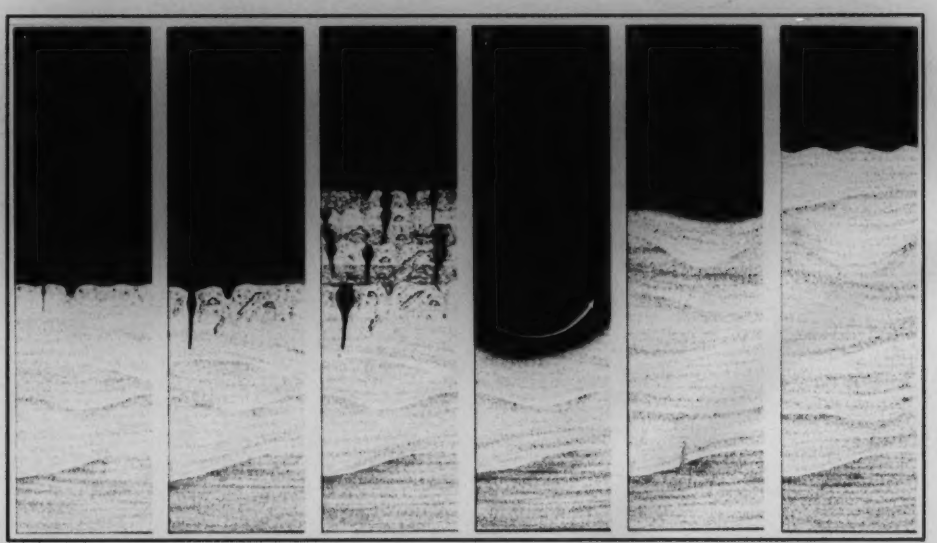


Figure 3.6 Diagram illustrating the idealized formation of amalgamated laminated storm beds. Fair-weather deposits, as depicted in panel 3, are regularly removed by subsequent storm scouring (panel 4). Shallow water depth, frequency of storms, intensity of storms, or a combination of the three, contribute to the amalgamation of storm beds. This sequence of events is speculated for the development of thick storm deposits characteristic of the Aklavik Formation (illustration generously provided by T. Saunders).

idea that the full spectrum of depositional conditions is not preserved in the rock record of the Aklavik Formation, due to storm scouring removing most, if not all, fair-weather activity.

3.5 Modern Analogue: the São Francisco Delta

The São Francisco River is the second largest river system in Brazil and is classified as a wave-dominated delta (Figure 3.7). A delta plain of 735 km^2 has been added to the coast, with only a small protrusion from the shoreline developing in the immediate vicinity of the river mouth (Coleman 1981). The strong wave action and littoral drift have redistributed the debouched sediments so effectively that the coastline has, overall, been straightened and made regular (Wright and Coleman 1973; Coleman 1981). Furthermore, the strong wave activity has presumably played a large role in maintaining a single distributary channel that cuts through the delta plain (Coleman 1981). The average wave power is 30.4 ergs/sec per meter of coastline, which relates to more energy expended in 10 hours on the São Francisco coastline that in 365 days on the Mississippi River (Coleman and Wright 1975; Coleman 1981). As a result, the deltaic deposits of this system are more accurately described as marine or shoreface deposits, due to the overprinting of wave action on the coast. The sand bodies that result from this high energy are typically composed of clean, well sorted, quartz rich sands. The sands of the São Francisco shoreline deposits are comprised of 95 to 97% quartz (Coleman 1981). The landforms associated with this delta system include high, broad sandy beaches and shorefaces, commonly displaying stranded beach ridges,

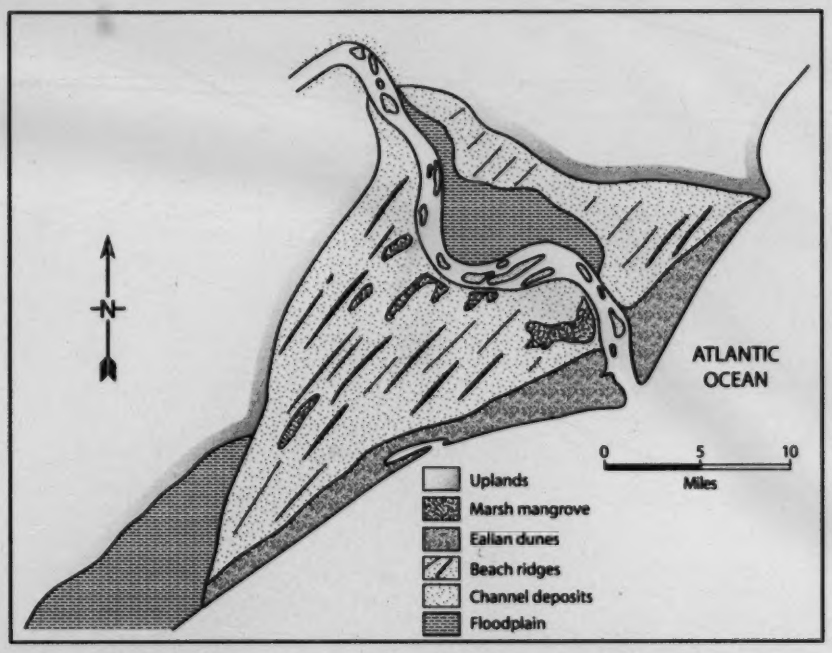


Figure 3.7 Geomorphology of the São Francisco Delta, classified as wave-dominated delta, and the modern analogue for the Aklavik delta (modified from Wright and Coleman 1973).

and large eolian sand dunes. This modern day system is an appropriate analogue for the Aklavik Formation, as both are characterized by high wave energy that results in the masking of deltaic deposits, with shoreface deposits being more characteristic.

Wright and Coleman (1973) identified that the greater the volume of discharge from the river, the greater the wave power required in order to rework the sediments into a wave-dominated configuration. The rock record of the Aklavik Formation holds evidence that the coastline was plagued with high energy waves, predominantly through storm activity, but presumably from large fair-weather waves as well. Therefore, the necessary high energy was present in order to modify the deltaic sediments into a laterally continuous, relatively smooth coastline. Generally, a more regular and smooth progradation of the delta shoreline (i.e. lacking barriers, spits, etc.) is favoured when the times of greatest discharge correspond to greatest wave power. Sediment volume of wave-dominated deltas with strong littoral drift is, as a result, more evenly distributed parallel to the general coastline trend (Wright and Coleman 1973). Flood waters, presumably carrying high sediment load, are associated with increased storm activity. This association leads to the speculation that, during deposition of the Aklavik Formation, the highest wave power would have been attributed to storms, thereby also being coupled with times of greatest discharge. Assuming a continuous sediment supply was available for the duration of Aklavik deposition, this association would have resulted in an overall smooth progradation of the shoreline. It also supports the observed lack of barrier bars within the shoreface. Additionally, had barrier bars developed, they would have been restricted to the immediate vicinity of the river mouth, and would have quickly been reworked and remolded by waves into the shoreface or beach deposits (Wright 1985).

Coastal deposits of the backshore environment, which generally have a low survival rate in the rock record, are not preserved in the Aklavik Formation, but conclusions can be made regarding their nature. The temperate northern setting, the abundance of available sand, and the occurrence of storms derived from high wind energy would have all contributed to a coastal setting dominated by large eolian dunes, similar to the coast of the São Francisco. Features that are more popularly associated with deltas, such as marshes and bifurcating distributary channels with inter-distributary bays, would not have developed along the exposed coastal plain, since these features are typical of river-dominated systems. The wave-dominated regime of the Aklavik delta produced long, linear, stranded beach ridges, creating an overall thick and highly continuous sheet of shoreface sands that prograded into the basin. It is this thick, laterally extensive sand package that makes up the Aklavik observed in outcrop today.

Figure 3.7 is a schematic representation of the São Francisco delta. From a geomorphological standpoint, the coastal setting during deposition of the Aklavik Formation would have largely resembled the coast of the São Francisco. It is important to note that the climate of the Aklavik delta differed greatly from the São Francisco Delta, which is located in a humid, tropical environment, and that the sediment supplied to the system is of a mixture of sand and mud. Also, the sourcing of sediment is not fully deltaic, with significant amounts of sand on the updrift side of the delta derived laterally from reworked older lowstand shelf sands (Dominguez 1996). Aside from these differences, the São Francisco Delta is an appropriate modern analogue for the this study based on the high wave activity, strong littoral drift, lack of bifurcating distributaries, and overall

geomorphological appearance. All of these characteristics are similar to what is predicted for the Aklavik delta.

Recent work by Bhattacharya and Giosan (2003) suggested that facies of wave-dominated deltas are more complicated then previously thought, and a new, more detailed classification system is warranted. Within this new research, the São Francisco Delta is considered an asymmetrical wave-dominated delta, where facies in the downdrift region of the river differ from the facies of the updrift region. The sandy, wave-dominated deltaic succession is more typical of the updrift flank, and is characterized by sediments that are commonly texturally mature sands that are derived from the reworking of older deposits, possibly low-stand shelf sands. Facies of the downdrift flank are typically the more irregular, fluvial-dominated succession, and characterized by sediments that are generally less texturally mature and more mud-dominated. This classification of asymmetrical wave-dominated deltas appears to be successful for many modern systems, where there is a significant supply of mud to the system (Bhattacharya and Giosan 2003). When examining the Aklavik Formation, where the sediment supply was dominated by relatively texturally mature quartz sand and an overall lack of mud, as well as the overprinting of deltaic deposits by storm influence, the symmetry of the delta cannot be inferred with confidence. As a result, the classical interpretation of the São Francisco Delta as the type example for wave-dominated deltas is sustained for this study. However, it is appreciated that wave-dominated deltas are more complicated than previously recognized, and that future detailed work on the Aklavik Formation may lead to the invalidation of the São Francisco as a modern analogue.

3.6 Stratigraphic Architecture

Previous work of the Bug Creek Group based correlations heavily on lithostratigraphic concepts. For example, the base of the Aklavik Formation is identified where the bluff forming sandstone cliffs outcrop, even though the Aklavik Formation combined with the underlying silty-sandy Richardson Mountains Formation can be considered as a continuous coarsening upward succession, and possibly a single parasequence, as defined by Van Wagoner *et al.* (1988) and Van Wagoner *et al.* (1990). The purpose of using lithostratigraphy is based upon easily recognizable contacts between formations as well as ease of mappability in the field. The use of lithostratigraphy is also very helpful in the subsurface (see Dixon 1982), specifically due to the sparse well control and the overall lack of good quality cores in the Bug Creek Group.

For the purpose of this study, sequence stratigraphic concepts were used due to the relatively close proximity of many of the measured sections. Surfaces of sequence stratigraphic importance were recognized in some of the eastern sections. These surfaces initiated the sequence stratigraphic correlations, which were commonly inferred both in a basinward direction and into the subsurface, which is generally considered to be landward. The most obvious surface identified in the field was a transgressive surface of erosion (TSE) (as previously mentioned in Chapter 2, Facies J Interpretations). The scouring and reworking of underlying sediments, namely Facies I, identified as reworked distributary channel deposits, created this surface. The result was exhumation of the strata, followed with colonization by a community of burrowing organisms, creating the densely bioturbated *Glossifungites* suite that demarcates this surface. Local occurrences of a transgressive lag are also visibly associated with this surface.

More than one TSE can be created during an episode of transgression; as a result, these surfaces are highly diachronous and are generally not the most reliable for correlation purposes. Consequently, the identified TSE in sections 9 and 11 was not considered as a datum. Instead, the surface of initial transgression (IT) was chosen as a more reliable datum (Figure 3.8). The surface of initial transgression was defined by Walker (1990) as the surface first recording modification of sediment by transgressing waves. This surface can also be described as a TSE, but is typically better constrained to a single time period. As Figure 3.8 illustrates, this datum delineates a shift from prograding and aggrading deposits of a highstand systems tract below (identified as deltaic influenced shoreface sands) to retrograding deposits of a transgressive systems tract above (identified as reworked distributary channel sediments). An observed shift in stacking patterns is also associated with this surface. This change is expected, as highstand deposits are commonly characterized by progradation, or a basinward shift in facies, and transgressive deposits are characterized by retrogradation, or a landward shift in facies (Emery and Myers 1996).

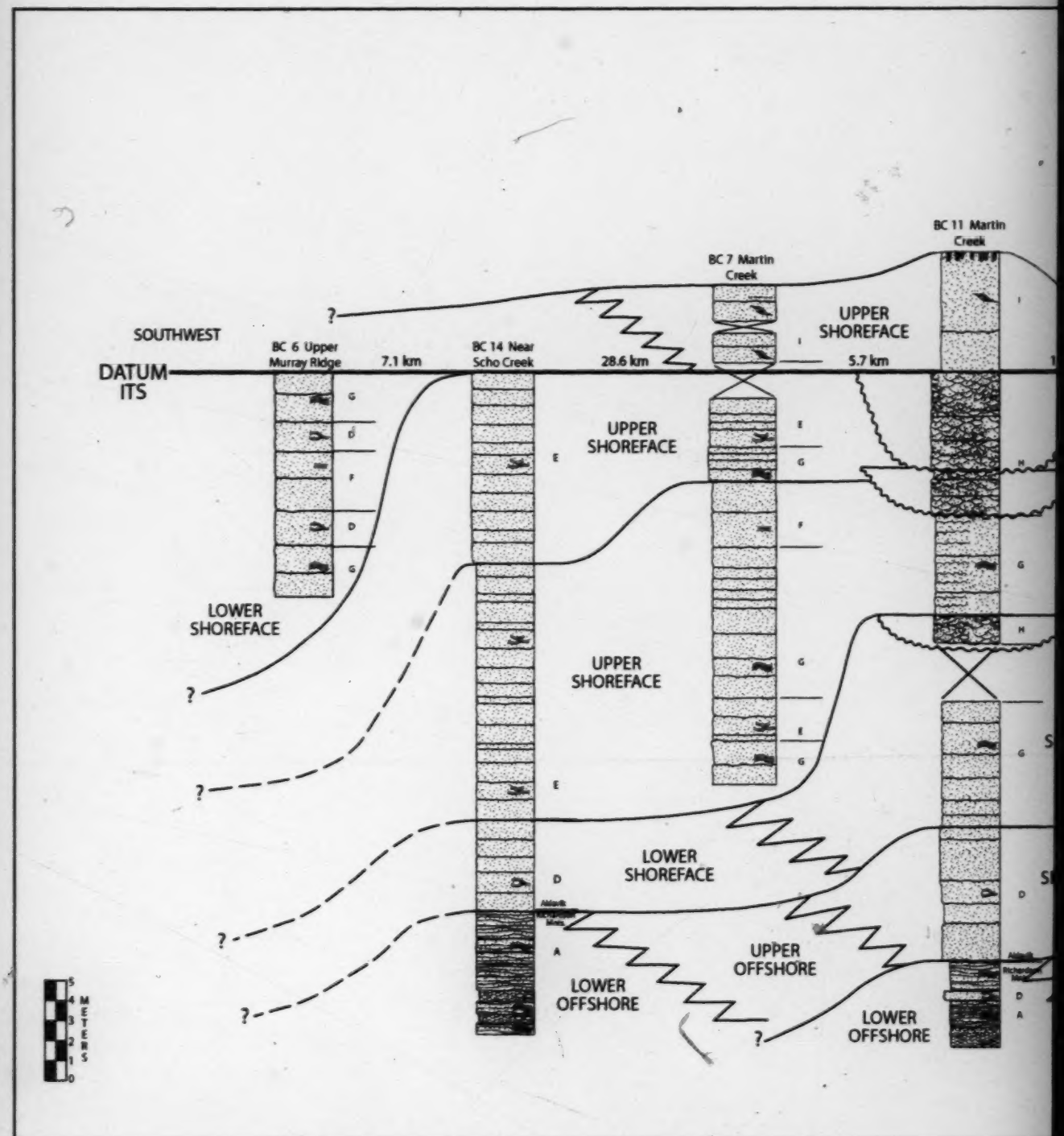
Figure 3.8 is a cross-section trending southwest-northeast across the study area, and incorporates a single subsurface data point, the Beaver House Creek H-13 well. The line of section is illustrated in Figure 1.1 of Chapter 1. Measured sections representing the most reliable data were chosen for the cross-section, and therefore the line of section does not necessarily appear as the most logical. Parts of six different shoreface deposits were identified using sequence stratigraphic concepts. These stacked shorefaces are inferred to represent different times of deposition, with the lower five packages reflecting the autocyclic nature of the deltaic environment. Autocyclic controls specific to this setting include pulses in sedimentation rates, local subsidence due to sediment loading, or creation of new beach ridges along the strandplain, a result of storm erosion and sedimentation, as well as fluctuating sedimentation rates and longshore currents (Psuty 1967). A single factor or a combination of these factors could have contributed to the progradation of a new shoreface.

The transition from T3 to T4 in Figure 3.8 represents a shift from prograding to aggrading shoreface deposits. This shift in stacking patterns reflects conditions in the basin that changed from sedimentation rates *outpacing* the creation of accommodation space, to sedimentation rates *equaling* the amount of accommodation space being created (Emery and Myers 1996). This fluctuation within the highstand systems tract is the result of autocyclic controls. Whether aggradation occurred due to sedimentation rates slowing overall or due to increasing rates of subsidence, and therefore increased accommodation space, cannot be definitely determined.

The effects of allocyclic controls are also evident from the cross-section and interpreted facies. The shift from highstand to transgressive systems tract (marked by the datum, or surface of initial transgression) is visible not only across the study area, but everywhere where the Aklavik Formation is observed, surface and subsurface (Figure 3.8). This change is interpreted as the result of a relative sea level rise, corresponding to a significant increase in accommodation space in the basin. Throughout the history of the Brooks-Mackenzie Basin, extension was the dominant tectonic regime, presumably due to active rifting (Balkwill pers. comm. 2002). This rifting created vast amounts of accommodation space for thick sediment packages to accumulate. Sedimentation rates during deposition of the Aklavik Formation were able to keep pace with the slowly increasing accommodation space, which corresponded to gradual rifting processes. However, the end of deltaic deposition, and consequently the end of the Aklavik Formation, resulted from a large

Figure 3.8

Stratigraphic cross-section of the Aklavik Formation across the study area from the southwest to the northeast. The line of section is illustrated in Figure 1.1 (Chapter 1). The datum used is the initial transgressive surface (ITS). Note vertical scale in the bottom left corner; horizontal distances are marked. This section illustrates that the Aklavik Formation and associated strata represent a succession of stacked shorefaces, with each individual shoreface represented as a single time period; i.e. Time 1 (T1) through to Time 6 (T6). T1 through to T5 represent progradational or aggradational shorefaces, which comprise the highstand systems tract. The division between T5 and T6 is marked by the surface of initial transgression, and also defines the shift from highstand to transgressive systems tract. The transgressive surface of erosion (TSE) is highlighted in red, and is represented by the *Glossifungites* surface identified locally at the top of Facies I.


SOUTHWEST
DATUM
ITS
BC 6 Upper
Murray Ridge
7.1 km
BC 14 Near
Scho Creek
28.6 km
BC 7 Martin
Creek
5.7 km
BC 11 Martin
Creek
UPPER
SHOREFACE
UPPER
SHOREFACE
UPPER
SHOREFACE
LOWER
SHOREFACE
LOWER
SHOREFACE
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OFFSHORE
LOWER
OFFSHORE
LOWER
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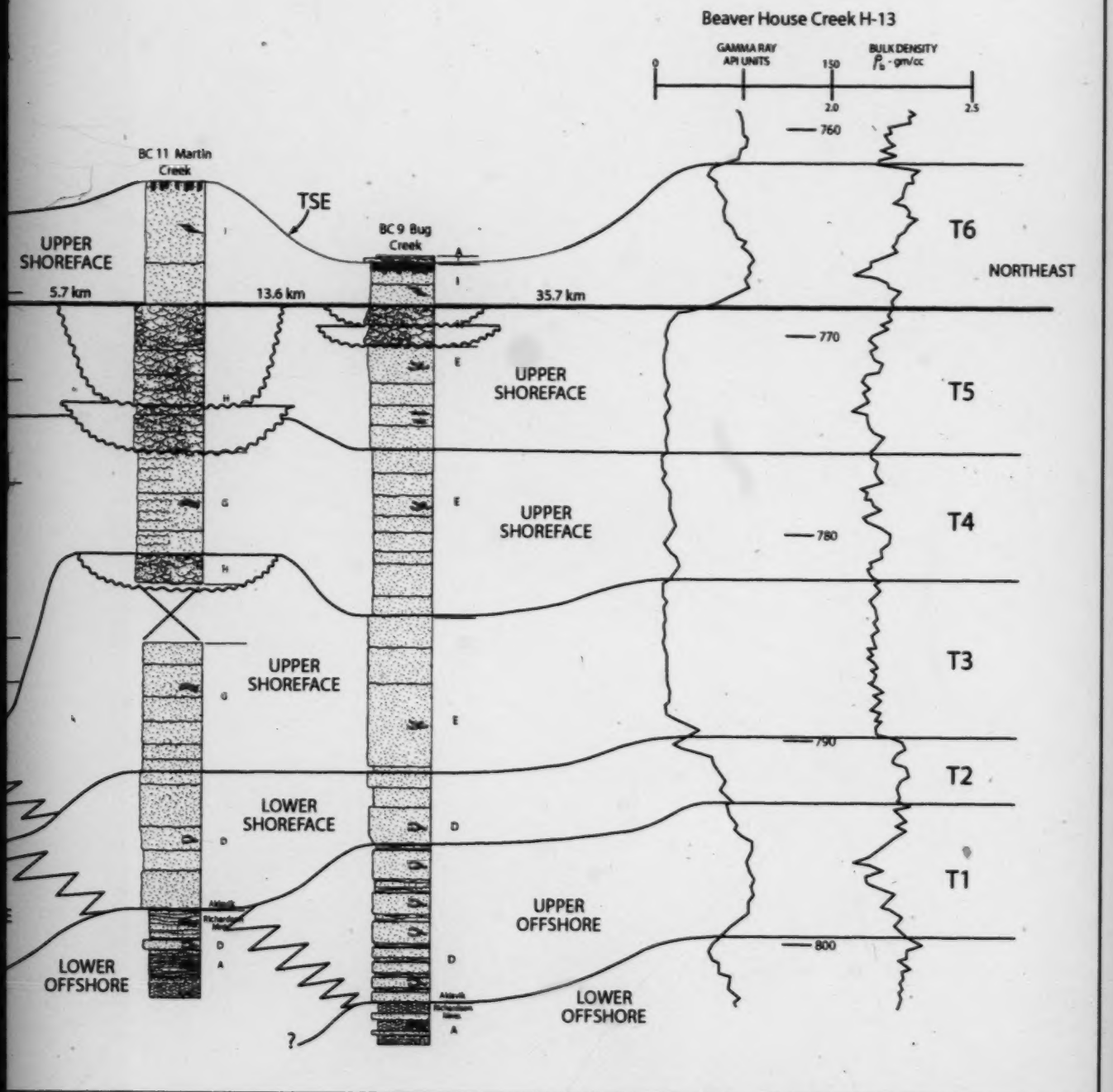
5
4
3
2
1
0


Beaver House Creek H-13
GAMMA RAY API UNITS
0
150
BULK DENSITY ρ_b - gm/cc
2.0
2.5
760
770
780
790
800
BC 11 Martin Creek
BC 9 Bug Creek
TSE
UPPER SHOREFACE
5.7 km
13.6 km
35.7 km
NORTHEAST
T6
T5
T4
T3
T2
T1
UPPER SHOREFACE
UPPER SHOREFACE
UPPER SHOREFACE
LOWER SHOREFACE
UPPER OFFSHORE
LOWER OFFSHORE
LOWER OFFSHORE
?

and sudden increase in accommodation space that allowed for widespread transgression. This allocyclic rise in relative sea level also corresponds well with eustatic sea level curves published for the Jurassic (Vail *et al.* 1984; Haq *et al.* 1987; Hallam 1988), which indicate a long-term eustatic sea level rise continuing through the Oxfordian and reaching a peak during the Kimmeridgian.

Heward (1981) noted that wave-dominated deltas commonly occupy structural lows, for example the down-thrown sides of growth faults. It is very probable that this was the structural setting during the Aklavik Formation, with the Eskimo Lakes Fault Zone, or its associated equivalent, controlling sedimentation. The extensional tectonic regime associated with active rifting that is already speculated regarding the Jurassic supports this interpretation. Also, coastal deposits of any type are typically better preserved within slowly subsiding basins (Davis and Clifton 1987). Therefore, the extensional system during deposition of the Aklavik Formation contributed to the overall high quality preservation of the shoreface deposits.

Braman (1985) stated that the marine shelf during deposition of the Husky Formation was parallel to a major fault zone, the Eskimo Lakes Fault Zone. This fault zone was presumably active during deposition of the Husky Formation, and is somewhat in trend with the interpreted shorelines of the Aklavik Formation (see Chapter 1, Figure 1.6). It is possible that the Eskimo Lakes Fault Zone affected sedimentation during the Late Jurassic, as well as heavily influenced the onset of transgression that ceased deposition of the Aklavik Formation.

The trend of the cross-section is roughly oblique to strike, and depicts facies changes from the northeast to the southwest that represent a progressive deepening into the basin (see Figure 3.8). The variability in the facies changes reflects the shifting configuration or trend of the shoreline. As a result, some shorefaces show progressive deepening of facies moving towards the southwest. This outcome is described as a more dip-oriented view, and can be observed in T1, T2, and T3. Other examples are more consistent across the section, showing little to no facies changes. T4 and T5 demonstrate this feature, and are better described as more strike-oriented views. The change in views between T3 and T4 suggests that at this time the orientation of the shoreline was modified, presumably the result of varying longshore currents in the basin or fluctuating point sources.

This cross-section is useful for predicting the occurrence of facies outside of the study area. It can be inferred that distributary channel deposits, similar to Facies H, would be associated with shorefaces T1 and T2 in a landward direction. Also, thicker distributary channel deposits may be found in a more landward position within shoreface T3. The lack of channel deposits during T6 supports the interpretation that transgression, resulting from a relative rise in sea level, caused the termination of active deposition of the Aklavik delta. Overall, considering the thick deltaic sandstones that characterize the Aklavik Formation in outcrop, it can be expected that continuing in a landward direction, less marine influenced and more non-marine influenced facies would be found. However, even though fluvial deposits are typically anticipated with this type of depositional setting, their preservation potential is generally much lower. Therefore such facies may have not survived the effects of transgression.

3.7 Subsurface Relationships

For the purpose of effectively completing this study, it is necessary to mention, even if briefly, the extension of the Aklavik Formation into the subsurface. As the subsurface occurrence of the Aklavik Formation is not fully discussed in this study, the reader is recommended to Dixon (1982). The southwestern region of the Mackenzie Delta is the site of where rocks of the Bug Creek Group extend into the subsurface. Typically the five formations of this group are not identified separately, but are rather lumped together and simply termed the Bug Creek Group. These rocks have possibly been penetrated by up to fourteen wells (see Chapter 1, Figure 1.1). The uncertainty associated with their correct identification is basically a product of sparse well control, complex faulting in the area, as well as the ambiguity associated with some of the biostratigraphic samples (Bever pers. comm. 2002). Depositional and thinning trends of several formations in the Bug Creek Group suggest that the southern depositional margin for the Jurassic was in the vicinity of the F-38 well, possibly associated with the Eskimo Lakes Fault Zone that trends nearby (see Chapter 1, Figure 1.6).

Gamma-ray log signatures of the upper Bug Creek Group largely depict the observations of the Aklavik Formation in outcrop; in other words, the thick sandstones appear to extend into the

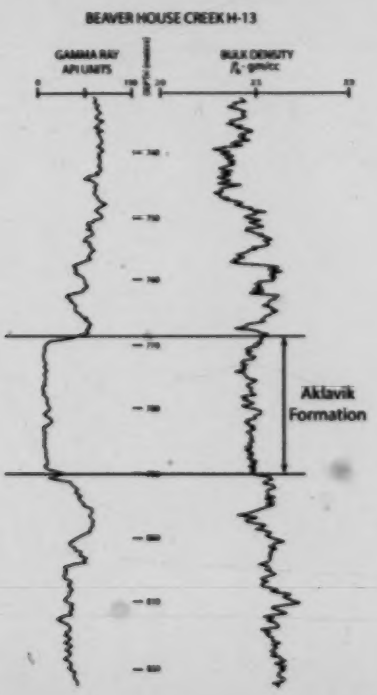


Figure 3.9 Typical well log signature of the Aklavik Formation, taken from the Beaver House Creek H-13 well, with gamma-ray and bulk density well logs shown. The top and base of the Aklavik Formation are identified, as defined by Dixon (1982). The depth is in meters.

subsurface. Figure 3.9 represents a typical well log signature of the Aklavik Formation, and is taken from the Beaver House Creek H-13 well, also included in the cross-section. The top and base of the Aklavik Formation are also depicted in Figure 3.9, as identified by Dixon (1982). The purpose of the cross-section is to illustrate a sequence stratigraphic interpretation of the Aklavik Formation. As a result the upper portion of the underlying Richardson Mountains Formation in the H-13 well was included in order to present a more complete picture. As well, sandstone beds that are controversial, and typically associated with the base of the Husky Formation, are included in the Aklavik interpretation. The biostratigraphic data for these formations suggests that there were no major hiatuses during deposition (Poulton *et al.* 1982), therefore including these extraneous strata into the illustrated interpretation is not impossible.

The rationale for including a single subsurface well in the cross-section for this outcrop study was not only to reconfirm that the Aklavik Formation does extend into the subsurface, but also to demonstrate the challenge of correlating detailed facies within a predominantly sandstone unit into the subsurface, specifically with geophysical well logs as the primary data source. Identifying stacked shorefaces within a thick sandstone unit in the subsurface, especially without the presence of complete core, becomes nearly impossible to execute with a high degree of confidence. As a result, the interpretations and correlations that can be made from outcrop data may not necessarily be as diligently applied to the subsurface.

3.8 Summary

The Aklavik Formation is identified as a wave-dominated delta with attached shorefaces. The depositional setting during this time was highly influenced by storms, specifically intense winter storms. This is reflected in the facies and the recognition of a stressed trace fossil assemblage, identified as being comprised of opportunistic species. This depositional model can be compared with a modern day analogue, the São Francisco River in Brazil. Using this analogue, greater detail can be inferred about the Aklavik delta and exposed coastal deposits, which were not preserved, presumably due to the erosive effects of transgression.

Sequence stratigraphy was successfully applied to the Aklavik Formation, improving the predictive power of facies outside of the study area, specifically in the subsurface. Two systems tracts were identified: the upper portion of a highstand systems tract, and the lower part of a transgressive systems tract. The progression from highstand to transgression marks an allocyclic change to the system, interpreted as a relative rise in sea level due to growth faulting affecting the basin. Autocyclic changes were also identified, resulting in a stacked shoreface succession comprising the thick sandstone of the Aklavik Formation. This thick sandstone unit continues into the subsurface and can be easily identified from well logs. However, the facies that comprise it, and therefore the evidence for the depositional setting, cannot be easily deciphered.

CHAPTER FOUR: PETROLOGICAL ANALYSIS AND DIAGENETIC HISTORY

4.1 Introduction

Textural and compositional data, based on modal estimates, were obtained from over 115 thin sections and 7 scanning electron microscope (SEM) samples in order to identify the main components of the diagenetic sequence for the Aklavik Formation. Previous workers have conducted petrographical studies on this formation (Young 1973; Poulton *et al.* 1982), but to the knowledge of this author, the diagenetic history of the Aklavik Formation has never been previously described in detail.

4.2 Classification and Textural Analysis

The Aklavik Formation is predominantly composed of pure, monocrystalline quartz, as previously identified by Young (1973) and Poulton *et al.* (1982). The samples examined from the study area can be classified, based on McBride (1963), as quartz arenite to sublitharenite (Figure 4.1). Typically, only minor amounts of accessory minerals are present, ranging between 5 and 10%. These minerals, listed in decreasing abundance, include chert, feldspar, kaolinite, polycrystalline quartz (metasedimentary rock fragments), various unidentifiable clays, chalcedony, heavy minerals such as tourmaline and zircon, and rare micaceous flakes. The quantity of the accessory minerals tends to decrease upward in section, resulting in the purest arenites associated with facies E, H and I, which are characteristically found near the top of the succession. This cleaner appearance

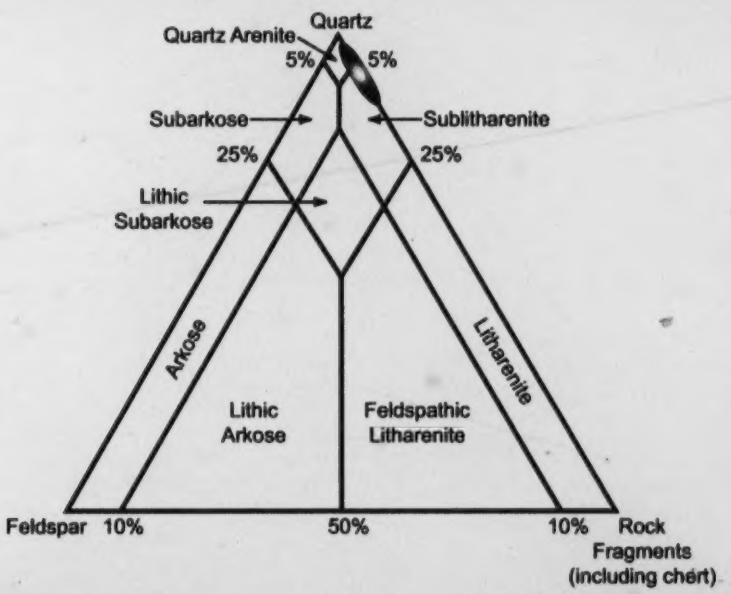


Figure 4.1 Classification of sandstones after McBride (1963). The composition of the sandstones of the Aklavik Formation fall within the quartz arenite and sublitharenite categories, based on modal estimates of 115 thin sections.

reflects the influence of the hydrodynamic processes that were responsible for the deposition of these facies, specifically in the form of high-energy waves reworking the sediments. The larger amount of accessory components is generally associated with facies D, and somewhat with F and G. The abundance of accessory minerals in these facies, which were identified in thin sections, indicates that they should be classified as sublitharenites. In some samples within facies E, the overall appearance of the composition is quartz arenite. With careful examination of the larger intergranular pores and partially dissolved grains, it is apparent that the rock has become a quartz arenite through diagenesis, and was most likely a sublitharenite in original composition.

The monocrystalline quartz grains (Figure 4.2 A) generally show non-undulose extinction and little evidence for strain. Many quartz grains contain inclusions that are commonly aligned, creating a cloudy appearance (Figure 4.2 B). These inclusions presumably consist of a combination of globules of gas and fine micaceous and opaque dust (Haverslew pers. comm. 2003). The sandstones within the Aklavik Formation are typically composed of well to moderately sorted, subrounded to rounded equant grains (Figure 4.2 C). An exception to this is the sediments from Facies J, which are commonly poorly sorted with subangular grains. Facies H frequently has a bimodal texture, with each mode being well sorted within it (Figure 4.2 D). This texture is the main reducer of porosity for facies H, due to restriction of the pore throats by the smaller grain size. The coarse grained facies commonly have high porosity (estimated at 15%) and permeability values, especially in the Martin Creek region, as there are very limited effects from chemical compaction or overgrowth development. Outside of the Martin Creek location, the Aklavik typically shows quartz overgrowth cementation, and increasing effects of chemical compaction, which are most obvious in the western region of the study area. These two processes combine to be the major reducing factor of porosity, and are discussed in more detail below.

The second most abundant component of the Aklavik Formation in the study area is chert, albeit a minor component (typically <15%), even within the sublitharenites. The chert composition can be difficult to distinguish in many samples, due to the dissolution level of individual grains (Figure 4.2 E, F). Where identifiable, it is a pure chert, composed of microcrystalline quartz that can be easily recognized under the microscope with crossed polars. Chert is readily distinguished from the rare, partially dissolved chalcedony grains and polycrystalline quartz grains that are present within the Aklavik Formation (Figure 4.3 A, B). These grains are characteristically associated with the sublitharenites of Facies D. Commonly, they are metasedimentary rock fragments that are identified by their undulose extinction, the result of internal suturing and strain. Both the chert and chalcedony grains show the effects of leaching by aggressive pore fluids, but are typically only partially dissolved, creating intra-granular porosity. This secondary porosity is generally limited, but still adds to the overall porosity network of the rock.

The small amount of feldspar (<10%) that is present in the Aklavik Formation is presumably potassium feldspar, but accurate identification is inhibited by the dissolution that normally affects these grains (Figure 4.3 C, D). The assumption that it is potassium feldspar is based on two reasons (Tuker 1991). First, potassium feldspar is more stable than plagioclase, and is therefore somewhat more resistant to alteration. Second, potassium feldspar is much more common in continental basement rocks, which are frequently the provenance of many sandstones. As a result, potassium feldspar is more abundant in sandstone than plagioclase. The entire feldspar component of the

Figure 4.2

A. Fine-grained porous quartz arenite sandstone, weakly cemented by pressure solution. The sample is comprised dominantly of monocrystalline quartz (Qtz) with few chert grains. Quartz overgrowths (OG) identified by sharp crystal faces. Small amounts of bitumen (Bt) are observed in the pore spaces (Pr).

B. Fine-grained quartz arenite. Quartz crystals commonly have a cloudy appearance due to aligned fluid inclusions (FI). Bitumen (Bt) stain partially occludes some pore space. Originally, the bitumen was preserved as a lining around detrital grains, but thin section preparation has caused the lining to detach. Clay material has collected to form linings along grains.

C. Well-sorted quartz arenite. Note the abundance of rounded, equant grains. This sample is from facies H; the sorting reflects deposition by wave processes. Rare heavy minerals (HM) can be identified; specifically this photo shows a possible tourmaline.

D. Quartz arenite with a bimodal texture. The sandstone is composed of subrounded, sorted, medium-sized detrital quartz and rounded, sorted fine-grained detrital quartz. This sample is exceptionally porous; porosity generally created by dissolution of a possible early phase calcite cement, leaving behind inter-granular pore spaces. Partial dissolution of a detrital grain has created moldic porosity (MP).

E. Partial dissolution of chert grains creates secondary porosity. Bitumen (Bt) partially occludes secondary pore spaces.

F. SEM image of intra-granular porosity being created by chert dissolution. Quartz overgrowths (OG) are visible along grain boundaries of detrital quartz (Qtz).

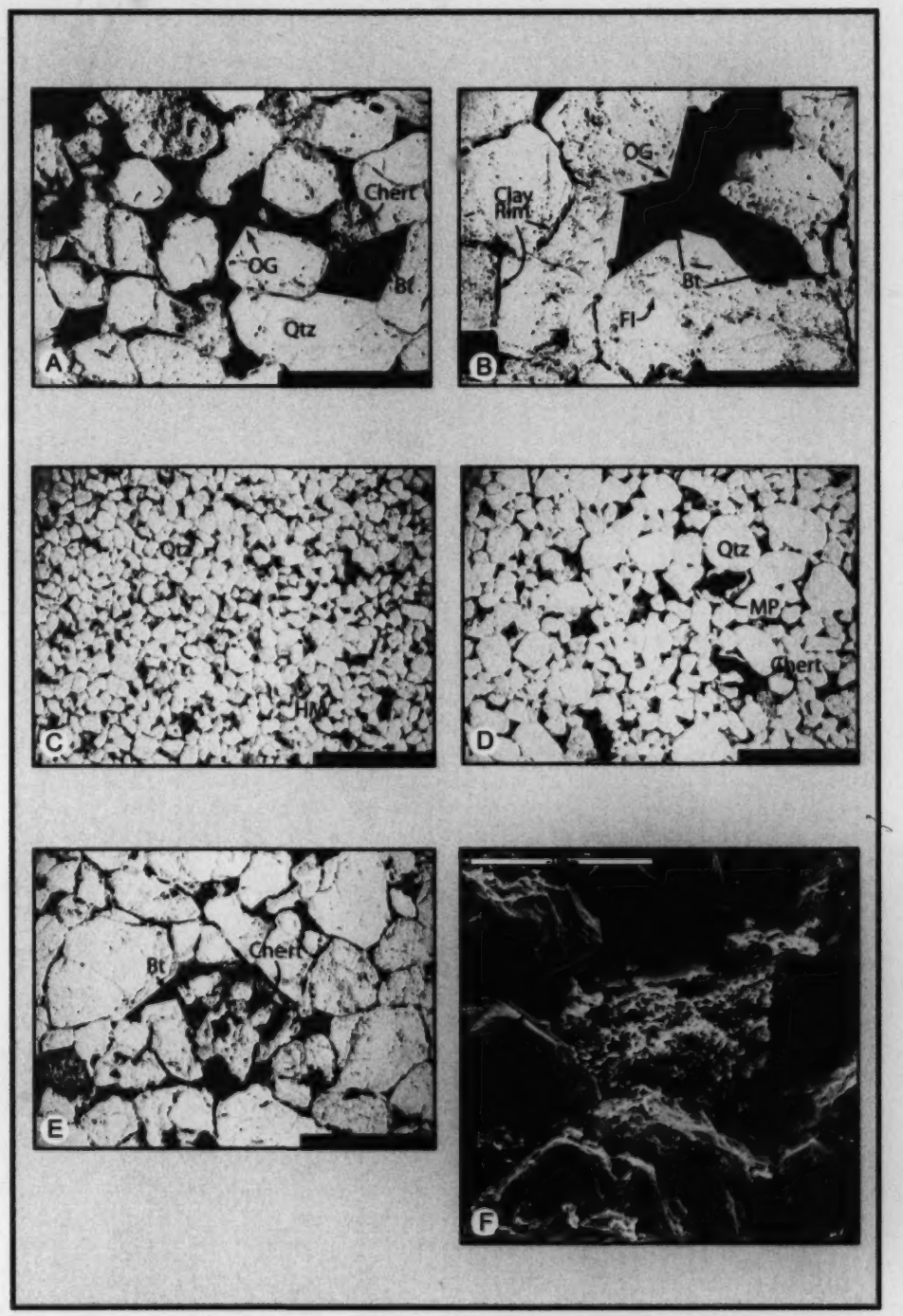

Chert
OG
Bt
Qtz
A
OG
Clay Rim
Bt
Fl
B
Qtz
HM
C
Qtz
MP
Chert
D
Bt
Chert
E
F

Figure 4.3

A. Partial dissolution of a chalcedony grain (Chdy), creating secondary porosity. Fluid inclusions (FI) can be seen within the detrital quartz grains.

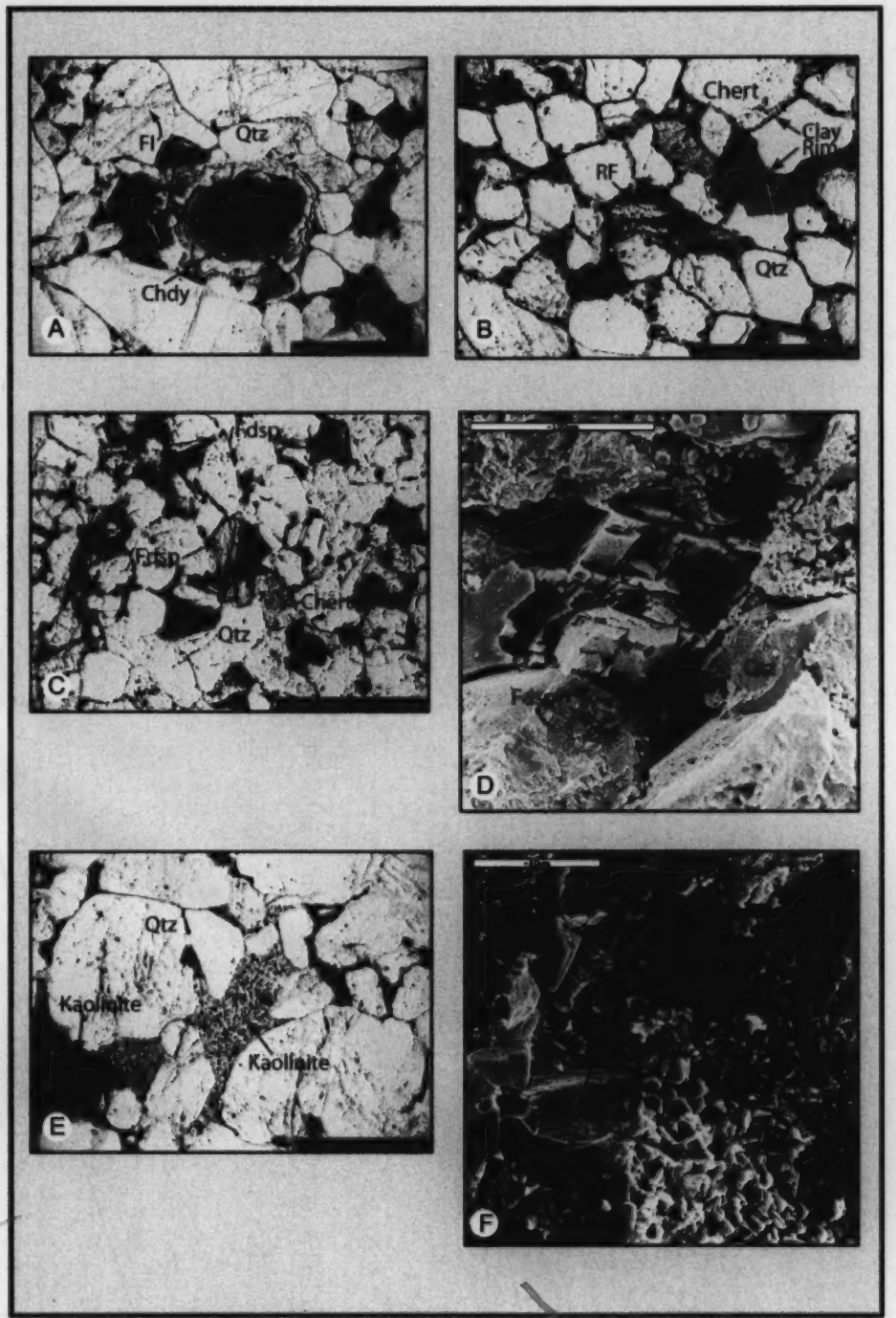
B. Sublitharenite sandstone, with monocrystalline quartz (Qtz), chert, and silicate rock fragments (RF). Clay rims line the detrital grains, and partially occlude pore spaces. The occluding clays are evidence that the pores are the result of dissolution of framework grains, and are therefore not primary.

C. Fine-grained sublitharenite with partial feldspar (Fdsp) dissolution. The result is intra-granular pores and an increase in secondary porosity.

D. SEM image of a partially dissolved grain of feldspar. Minor amounts of clay particles are visible, but are most likely not the result of feldspar alteration.

E. Fine to medium-grained quartz arenite with kaolinite filling pore space, and partially occluding pores to the left. Where it is present, kaolinite effectively reduces or eliminates porosity; but it is observed in such small quantities that it is not considered a major porosity-reducing factor. The dark particles within the clay may be due to staining from bitumen.

F. SEM image of well formed books of authigenic kaolinite. Note the lack of quartz overgrowths (sharp crystal faces) on the quartz grains; the development of overgrowths was hindered by the presence of kaolinite.


Fl
Qtz
Chdy
A
Chert
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RF
Qtz
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Fdsp
Fdsp
Chert
Qtz
C
D
Qtz
Kaolinite
Kaolinite
E
F

sandstones shows the effects of aggressive pore fluids, with the results ranging from partial to total leaching of the grains. This reflects their unstable nature under relatively deep burial diagenetic conditions (Folk 1980). The main products of this leaching are intra-granular or moldic pores, creating a secondary pore system. In some regions of the study area, where quartz cementation from pressure solution has welded the grains together, this is the only form of porosity present (Figure 4.4 A). Relative to the quartz grains, the feldspar grains are typically smaller (for example, very fine-grained within a fine-grained matrix of quartz), reflecting their lower durability during conditions of transport or reworking.

Clays constitute a minor component of these sediments, with kaolinite being the most abundant type. Kaolinite within the Aklavik Formation is authigenic, forming through the precipitation of formation waters carrying needed aluminum (Carozzi 1993). Some kaolinite formation may be attributed to the breakdown and alteration of feldspar, but the evidence suggesting this as the primary producer of this clay is not sufficient. Kaolinite typically fills pore spaces, and occasionally lines inter-granular pores (Figure 4.3 E, F). Where it is present, it reduces porosity and permeability, but because of its low occurrence within the sandstones, it is not considered a major porosity-reducing factor. An unidentifiable lining of clay-like material can be seen along many grain boundaries, and essentially outlines the pores (Figure 4.4 B). The lining is presumably a combination of different interstitial clay particles such as illite, which has been previously recognized by Poulton *et al.* (1982) in older formations of the Bug Creek Group. Samples examined with the SEM did not indicate conclusive results, aside from the linings not being associated with an iron or titanium oxide. It is probable that the clays formed due to weathering or a surficial fluid flow event (Haverslew pers. comm. 2003). In some samples, the linings are relatively more significant in thickness, irregularly filling pore spaces, and possibly associated with a different phase of diagenesis. These examples have residual bitumen or bitumen stain associated with their composition (Figure 4.3 B).

4.3 Diagenetic History

Diagenetic processes begin immediately upon burial of the sediment, ultimately working to destroy or enhance porosity (Wilson and Stanton 1994). As the sediments are buried deeper, diagenetic reactions continue in the direction of greater mechanical stability through compaction, and of greater thermodynamic stability through mineral reactions (Bjørlykke 1994). For this study, six different processes were identified within the diagenetic sequence (Figure 4.5), and are outlined below. It is important to note that these processes did not occur as individual events, but took place over a continuum of time.

4.3.1 Mechanical Compaction

Due to initial, as well as continued, lithostatic pressure on the rock, pore fluid was expulsed from the rock and initial porosity was substantially decreased. Coinciding with mechanical compaction was the rearrangement of grains, resulting in a more stable packing framework. This is typical of all buried sandstones, and some workers believe that the more stable positioning can result in a porosity decrease from initial levels of 40 to 50% to 20 to 25% (Wilson and Stanton

Figure 4.4

A. Example of fine-grained quartz arenite to sublitharenite from western region of the study area (near Almstrom Creek). Note the general lack of pore space due to the welding of grains (WG) from pressure solution. The only porosity that may occur is secondary and rather insignificant, as seen by the partial dissolution of a single feldspar grain (Fdsp).

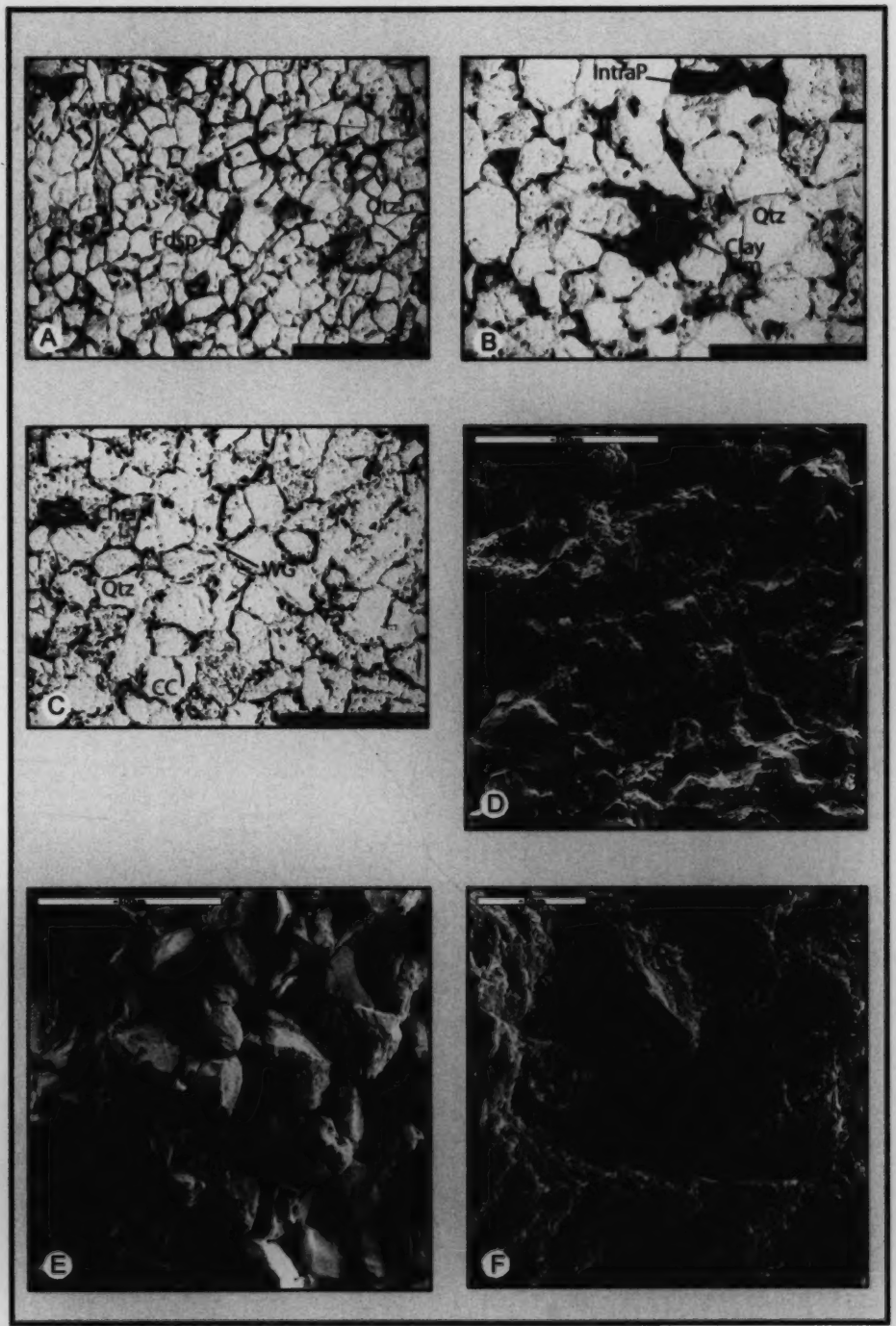
B. Fine to medium-grained quartz arenite with well developed secondary porosity types. The partial dissolution of a rock fragment creates intra-granular porosity (IntraP). Clay rims frequently outline pores, reflecting that pore space commonly results through the dissolution of framework grains.

C. Fine to very fine-grained quartz arenite to sublitharenite from the western region of the study area (Murray Ridge). Porosity has been fully eliminated through the development of quartz overgrowths and, for the most part, pressure solution resulting in welded grains (WG). Note the concave-convex grain boundaries (CC) as well as the frequent lack of grain boundaries altogether (WG).

D. SEM photograph of fine-grained quartz arenite to sublitharenite with abundant quartz cement, the result of pressure solution. The coating that covers most of the grains, making the individual boundaries indistinct, is the quartz cement.

E. SEM photograph of medium-grained, porous quartz arenite. Cementing predominantly due to quartz overgrowth development, with inter-granular pores (InterP) left open. Compare to Figure 4.4 D, which has very little porosity. Clay material lines some of the grains.

F. Tightly cemented sublitharenite showing secondary porosity resulting from dissolution of framework grains (DissP). Possible irregular grain boundaries (IRG) on detrital quartz grains may indicate minor silica dissolution.


Qtz
FdSp
A
IntraP
Qtz
Clay
B
Chert
WG
Qtz
CC
C
D
E
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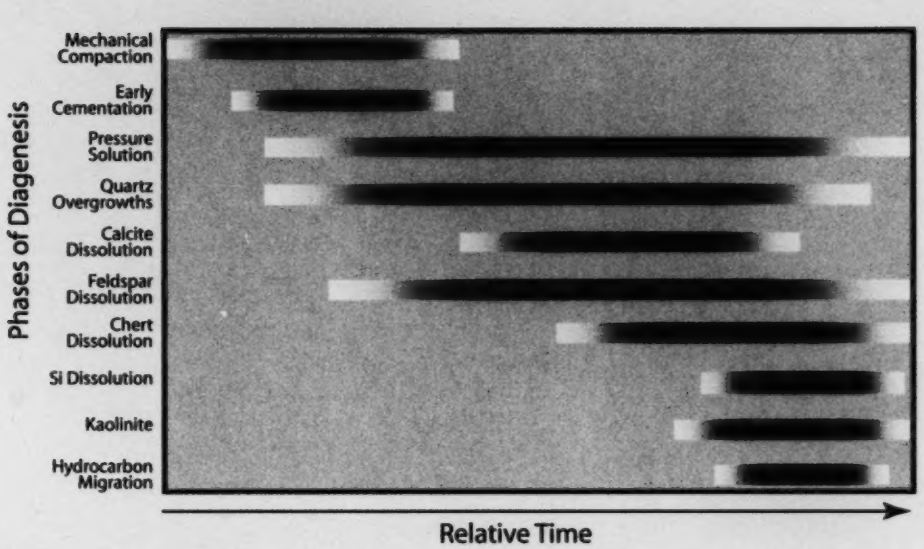


Figure 4.5 Relative timing of the different phases of diagenesis identified for the Aklavik Formation.

1994). However, considering the original sediments were well-sorted, well-rounded beach sands, the original porosity was presumably somewhat less than 40%, due to effective packing during deposition.

4.3.2 Early Cementation

An early phase of cementation, comprised of calcite, is proposed with speculation, due to the limited physical evidence, as well as lack of remnant calcite crystals. The presence of a calcite cement would have provided the necessary rigidity for the framework grains to withstand overburden stress and ensure preservation of primary porosity. Anomalously high porosity and permeability values are preserved within the coarser grained facies in the Martin Creek area, which may be attributed to early cementation. Specifically, facies H and I show very little evidence of quartz overgrowth development or chemical compaction, both of which are pervasive diagenetic phases in the Aklavik Formation aside from this region. The most plausible explanation for the observed anomaly is an early phase of cement, presumably a carbonate rather than an authigenic clay, that formed within the coarser grained facies, which are also the more shallowly buried sediments. This cementation phase would have happened prior to quartz overgrowth development and further cementation. The presence of an early carbonate cement prevented cementing by quartz during later diagenetic phases, thus prevented the significant reduction of porosity commonly attributed to the Aklavik Formation.

It is important to note that quartz cementation is most abundant in clean, quartz rich rocks that do not have early diagenetic pore filling carbonate cements (Worden and Morad 2000). This supports the argument that an early carbonate cement infilled much of the inter-granular pore space of the coarser grained facies, and prevented prolific quartz cementing. In the finer grained facies, the

carbonate cement was not present, and therefore quartz cementing and overgrowth development were fully active in reducing porosity.

Further, it is also somewhat uncharacteristic to have a coarse grained facies showing little evidence for quartz cement, when the associated fine grained facies has very limited porosity and appears to have experienced both quartz overgrowth development and pressure solution. Typically within inter-bedded fine and coarse-grained facies, the finer grained sands act as silica exporters. This is due to the effects of pressure solution, which frees silica to the pore waters, allowing it to be re-precipitated in the coarser grained sands; therefore the coarse-grained facies are considered silica importers (Houseknecht 1984). Section 4.3.3 discusses the diagenetic phase of quartz overgrowths and pressure solution in more detail.

Only a few of the sand grains of facies H appear to have pits and notches in them, which are best observed with the SEM (Figure 4.6 A, B). These surficial features are interpreted as the result of calcite corrosion, and are the only physical evidence for there ever having been a phase of calcite cementation. Calcite corrosion results from the instability of quartz under calcite-favourable conditions. A solution that is able to precipitate calcite has a high pH, since calcite is an alkaline mineral and stable under this condition. This type of environment is hostile towards quartz, as it is an acidic mineral and stable under low pH; the outcome is corrosion of the grain boundaries of the detrital quartz (Evoy pers. comm. 2003).

4.3.3 Quartz Overgrowth Cementation and Pressure Solution

The abundant quartz grains in the Aklavik Formation act as both a substrate for quartz precipitation, in the form of overgrowths, and as a source for silica, through the means of pressure solution, or chemical compaction (assuming a closed system for diagenesis of the Aklavik Formation). Therefore, it is probable that the processes of overgrowth development and pressure solution did not occur as individual events, but overlapped to a substantial degree; for this reason they are discussed together in this section. The most significant cause of porosity reduction in the Aklavik Formation is due to the combination of these two processes.

Worden and Morad (2000) noted that the probability of developing some type of quartz cement during diagenesis is greatly influenced by the composition of the rock. Based on this, it is not surprising that the most abundant form of cement for the arenitic and sublitharenitic sandstones is quartz (Figure 4.4 D).

Even though quartz cementation is a common occurrence during diagenesis, many of the controls, as well as the origin of cementation, are still the subject of much debate (see Wilson and Stanton 1994; Worden and Morad 2000). Some workers believe that precipitation of quartz overgrowths is most common during deep-burial diagenesis (>2.5 km) and with elevated temperatures, typically between 90 - 130°C (Worden and Morad 2000). The higher temperatures are necessary because of the solubility of silica, though silica cementing is still noted to occur at shallower depths. Worden and Morad (2000) summarized work on quartz cementation from numerous workers, and noted that it is possible to have considerable quartz cementation occurring over long time spans at relatively low temperatures, and conversely it is possible to have cementation which takes place over a shorter time span with higher temperatures. The subsidence history of the Jurassic is not fully

Figure 4.6

A. Irregular grain boundaries (IGB) on quartz grains, indicating possible evidence for an early phase of calcite cement.

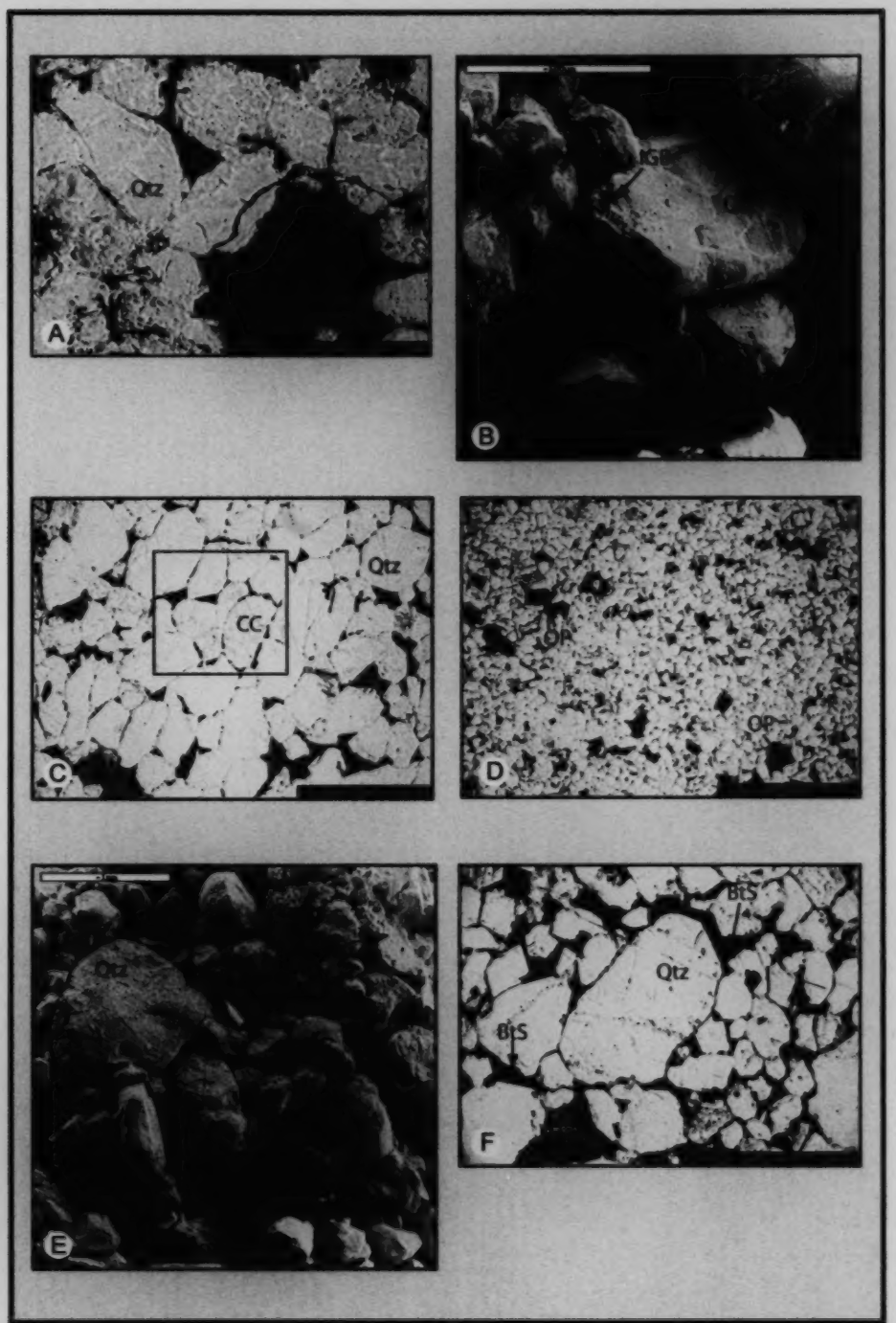
B. SEM photograph of irregular grain boundaries (IGB) on quartz grains within an arenitic sandstone with bimodal sorting.

C. Quartz arenitic sandstone with welded grains showing well-developed concave-convex grain boundaries.

D. Well-sorted sublitharenitic sandstone with oversized pores (OP), indicative of an early cement phase that has now been fully dissolved.

E. Inhomogeneous grain packing, with pores (P) near bottom of photo, and cement lining grains near the top. This packing style indicates that a once patchy authigenic cement was present, but has now been fully dissolved.

F. Bimodal sorting in a quartz arenitic sandstone. Bitumen stain (Bts) randomly occludes pore spaces to variable degrees.


Qtz
A
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Qtz
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C
OP
OP
D
Qtz
E
Qtz
BtS
BtS
F

understood for the Brooks-Mackenzie Basin (Norris 1997). Therefore it can only be suggested that some regions of the study area, where the effects of pressure solution are plentiful, may have been exposed to either high temperatures for a brief period of time, or lower temperatures that were still considerable for a long enough time span to allow for cementation to occur to the degree that it did.

The source of silica, whether it is internally or externally sourced, is also scrutinized regularly. Theoretically, it is possible to have external sources of silica, where transport distances can be many tens of meters to kilometers (Worden and Morad 2000). Bjørlykke (1994) argues that in order to advectively transport significant volumes of silica in aqueous dissolution, enormous fluxes of water are necessary. Improbable amounts of water, in the order of 10^8 cm^3, would need to pass through each cm^2 of rock. Because of the large amounts of water needed in order to accomplish externally sourced quartz cementation, Bjørlykke (1994) favours silica being sourced internally, or through the means of diffusion. Relative to the Aklavik Formation, internal sourcing of silica is the most evident explanation for cementation. The abundance of quartz in the sandstones, along with evidence of pressure solution in many of the samples, supports this notion.

Where quartz overgrowths are observed in the study area, they are found only on detrital quartz grains, and are typically isolated with well-defined crystal faces (Figure 4.2 A, B, F). In some samples, the original shape of the detrital grain is rounded, but the development of quartz overgrowths has produced a more angular look for many of the grains. The well-formed crystal faces of the overgrowths are easily seen with the SEM, and suggest that, at one time, sufficient inter-granular space, silica supply, and time was available for their formation. These overgrowths appear to form preferentially on monocrystalline quartz grains, allowing the remaining constituents to retain their original shape. This agrees with work done by James *et al.* (1986), who noted that quartz overgrowths are preferentially developed on monocrystalline quartz when compared to polycrystalline quartz grains. In most localities studied, quartz overgrowths terminate within the inter-granular pore space, resulting in a slight reduction in porosity, but a continued connectivity of pores.

Overgrowths are best identified under the microscope with the presence of dust rims. These develop between the interface of the original quartz grain and the overgrowth. Where these dust rims are absent, recognition of overgrowths can be difficult due to many of the crystals being affected by chemical compaction. Therefore the typically well-defined euhedral terminations of the overgrowths are not always observable. The challenge of identifying quartz overgrowths associated with quartz crystals is a result of the overgrowths having the same crystallographic and optical orientations as those of the original nucleating quartz grain (Carozzi 1993). Cathodoluminescence (CL), which highlights the boundaries between grains and syntaxial rims, is the most reliable technique for quartz overgrowth recognition (Carozzi 1993). Backscatter electron imaging on the microprobe, combined with CL, would better reveal the complexity of the overgrowths (Carozzi 1993). These methods should be utilized in order to better understand the silica cementation patterns in the Aklavik Formation. Such examination would reveal if several cementation episodes occurred, and would provide a record of changes in the chemistry of the formation waters through time.

Increasing pressure and temperature influences the progression of pressure solution, but the necessary catalyst for initiation is the presence of clay minerals or organics, generally found as grain coatings (Worden and Morad 2000) (Figure 4.2 B). Evidence of pressure solution was most apparent in the western localities of this study area, where quartz grains showed well-developed concave-convex boundaries (Figure 4.4 C; Figure 4.6 C). Figure 4.7 illustrates the two main types of grain boundaries common in the Aklavik Formation, as a result of pressure solution. In some samples, the degree of welding was so significant that individual grain boundaries could no longer be identified (Figure 4.4 C). The result was full elimination of porosity. The lack of fractured grains confirms that welding occurred through chemical, rather than mechanical, compaction. In a few samples, minor stylolites were present, reflecting a nucleation site associated with an organic lamination.

It is common for pressure solution and quartz overgrowth development to overlap during diagenesis (Carozzi 1993). The sandstones in the western part of the study area have had the two processes combine to such a great extent that it is typically very difficult to identify individual overgrowths. This is due to the suturing of grains and the concave-convex grain boundaries that are produced (Figure 4.4 A, C). The resulting texture of the extreme combination of these processes is termed quartzitic (Carozzi 1993), and can be used to describe the texture of the rocks in this part of the study area.

4.3.4 Dissolution and Development of Secondary Porosity

The development of secondary porosity is an important role in the diagenesis of sandstones, and as a result, the topic has been the focus of much research (see Hayes 1979; Pittman 1979; Schmidt and McDonald 1979a, 1979b; Harris 1989; Bloch 1994). Secondary porosity in the Aklavik Formation was most likely associated with more than one event of pore water migration. The presence of open pores suggests that the main episode of dissolution occurred after quartz cementation had ceased. Had dissolution taken place prior to the last phase of cementation, the newly created pores would have been in-filled with quartz overgrowths or cement. However, there is evidence that dissolution and cementation did overlap. Within facies H, examples of quartz overgrowths can

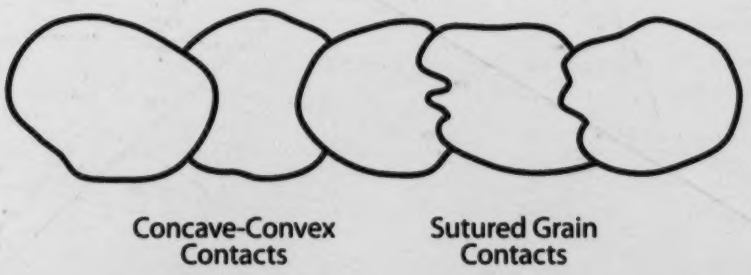


Figure 4.7 Schematic example of different grain contacts, resulting from pressure solution. Both can be seen in the Aklavik sandstones, but concave-convex is the more common of the two (modified from Jonas and McBride, 1977).

be seen protruding into secondary pores. These pores are interpreted to have been created by the dissolution of calcite cement, thereby allowing space for overgrowths to develop into.

Dissolution of the more soluble rock components began with the circulation of aggressive pore waters. The components most affected were calcite cement, which was fully removed, chert, feldspar, chalcedony, and rock fragments (Figure 4.2 E, F; 4.3 A - D). The partial or full leaching of these grains and cement allowed for the creation of larger inter-granular, intra-granular, and moldic pore textures, thereby increasing the overall pore network and permeability of the rock. For some of the facies, such as the finer grained examples previously mentioned, this is the only porosity that is present (Figure 4.4 A).

Minimal permeability was necessary within the Aklavik sandstones to allow for the migration of pore water. Fully cemented rocks do not offer a pathway for formation waters to travel, and consequently do not experience leaching and the development of secondary porosity to the same degree as permeable sandstones. Dissolution generally occurs under deep burial conditions by aggressive solutions rich in carbon dioxide, the result of decarboxylation of maturing organic matter in basinal shale units (Carozzi 1993). These solutions are corrosive to rock components that are not in equilibrium with diagenetic pressure, temperature, and pore-fluid chemistry. In order for an equilibrium state to be reached, the less stable components commonly undergo diagenetic alteration or dissolution (Worden and Morad 2000). Relating to the Aklavik Formation, the result of this was secondary porosity created by the leaching of framework grains or cement. This process was presumably responsible for the very minor silica dissolution, reflected by the presence of irregular grain edges and pitted boundaries (Figure 4.4 F).

Schmidt and McDonald (1979b) noted that secondary porosity can very closely resemble primary porosity, and outlined criteria for distinguishing between the two. The most common form of secondary porosity in the Aklavik Formation is partial dissolution of soluble grains. Where leaching has affected grains only to a small degree, intra-granular porosity results; chert and feldspar grains commonly demonstrate this feature, as does chalcedony (Figure 4.2 E, F; 4.3 A, C, D). In some samples, moldic porosity is observed, highlighted by a pore lining clay residue (Figure 4.4 B). Where these linings occur, they can be detrimental to permeability, as they are able to block pore throats and eliminate pore conductivity. Some of the less stable detrital grains show only minor amounts of dissolution effects in the form of corroded edges. Oversized pores (Figure 4.6 D), defined as pores that are generally one and a half times larger than the largest grain size (Schmidt and McDonald 1979b), are a common feature of the pore network within the coarse grained facies. Another feature, although not as frequent, is the appearance of loosely packed sediment adjacent to areas that have more closely spaced grains (Figure 4.6 E). This is termed inhomogeneity of grain packing and is indicative of secondary porosity that has resulted from the dissolution of once patchy authigenic cement. This porosity type, coupled with oversized pore spaces, generates the largest and most effective porosity and permeability within the Aklavik Formation. Unfortunately, this feature is facies specific, and Facies H is not laterally extensive across the study area.

4.3.5 Development of Authigenic Clay

Authigenic clay in the Aklavik Formation is preserved only in minor amounts, in the form of

kaolinite (Figure 4.3 E, F). Kaolinite can be seen randomly in all of the facies sampled, and appears to have preferentially crystallized within the larger pore spaces, fully occluding the porosity. Its presence is so limited that it is not considered a major reducer of porosity for the Aklavik sandstones. With the SEM, both well-developed, relatively pristine booklets of kaolinite crystals as well as some crystals with corroded edges could be observed (Figure 4.3 F). This suggests that kaolinite as a whole is stable at surface conditions, and that aggressive formation waters associated with dissolution may have attacked some of the kaolinite. Formation of the clay linings, of unknown composition, may have also occurred during this diagenetic phase (Figure 4.4 B, E). The evidence for this is the appearance that the clays coat the quartz overgrowths in some samples (Figure 4.6 C). The precise timing of these linings is unknown, but it is assumed to be associated with the migration of the formation waters that allowed for the crystallization of kaolinite.

4.3.6 Hydrocarbon Migration

The evidence for a diagenetic phase that included hydrocarbon migration is very limited, but certain samples suggest the presence of residual bitumen. This feature can only be observed with some certainty in one locality. It appears as black, opaque linings that are irregular in thickness, and adhere to grain boundaries (Figure 4.2 A, B). Thin section preparation has caused pieces of the lining to become detached from some of the grains, resulting in floating black debris within the epoxy. In some samples, the bitumen has a stain-like appearance, and randomly occludes pore spaces to variable degrees (Figure 4.6 F). The timing of this event, relative to kaolinite development, is unknown, as the residual bitumen was never observed in connection with kaolinite. The association of residual bitumen with both primary and secondary pore systems supports that migration took place after the creation of secondary porosity. Hypothetically, if migration of hydrocarbons did occur, it was the last phase of diagenesis prior to uplift and exposure of the Aklavik Formation in the Richardson Mountains.

4.4 Discussion on Provenance

Dominance of well sorted, rounded, monocrystalline quartz grains reflects the maturity of the sandstone, which most likely experienced a history of reworking, during which weaker or less stable varieties of quartz were gradually eliminated, presumably through transport and alteration. This supports the interpretation by Poulton *et al.* (1982) that the sandstones of the Aklavik are the result of numerous cycles of reworking. Consequently, it is challenging to identify the direct provenance of the Aklavik Formation.

Monocrystalline quartz is known to originate from either reworked older sandstones, plutonic igneous rocks and high-grade metamorphic rocks, or from phenocrysts of silicic volcanic and pyroclastic rocks (Carozzi 1993). The presence of chert suggests sourcing from the Permian aged Lower member of the Jungle Creek Formation, which is composed partially of breccio-conglomerate chert beds (Dixon 1998). This evidence, along with the vast amount of monocrystalline quartz within the Aklavik Formation, support the general hypothesis that the sandstones are sourced from multiple cycles of reworking of older clastic sources, most likely from Permian strata, as well as possibly Triassic strata, which are not present in the study area. The feldspars and polycrystalline quartz grains that make up a minor amount of the sandstone are not local in origin, and are somewhat problematic in their source. Poulton *et al.* (1982) suggest a possible origin for these

foreign sediments as the Precambrian "Grit Unit" of the Mackenzie Mountains, which may have been uplifted and exposed to erosion throughout the Jurassic. This provenance hypothesis suggests a minimum transport distance of 300 – 400 km. Sourcing from the Canadian Shield would require a minimum transport distance of 750 km or more (Poulton *et al.* 1982).

The coarse-grained sands of Facies H commonly show a bimodal texture. The bimodal nature of this facies reflects hydraulic sorting, considering the nature of deposition of the sands of the Aklavik Formation.

4.5 Subsurface Implications

Outcrop based predictions of subsurface reservoir quality are potentially less accurate than subsurface based predictions, because of the following limitations (Tobin 1997):

1. Reservoir facies exposed at the surface may have undergone a different tectonic and burial history than their subsurface counterparts
2. The diagenetic history may be different than the equivalent subsurface rocks
3. The composition and pore system characteristics may have been altered by recent outcrop diagenesis
4. Hydrocarbon shows are less likely to be preserved in basin-margin reservoir facies exposed in outcrop than in their subsurface counterparts; any shows that are present may be weathered away or severely biodegraded

It is important to note that the meteoric diagenetic environment is very harsh, and that rocks exposed at surface can have their burial history overprinted by meteoric diagenesis (Folk 1980; Carozzi 1993). However, porosity trends and characteristics can still be gathered from outcrop data from the Aklavik Formation, and applied to the subsurface, if only for the purpose of speculating on the reservoir potential of the subsurface.

There are two main porosity trends associated with the Aklavik Formation: a porous and a non-porous trend. Generally, facies are tightly cemented and show evidence for chemical compaction. This feature is widespread across the study area, but is typical of outcrop exposures in the western region. The composition of the rock, quartz sublitharenite to arenite, generally favours abundant silica cementation during diagenesis, due to the large supply of silica available. The second trend consists of highly porous quartz arenitic sandstones, associated with Facies H and I. This trend is localized to the Martin Creek region of the study area, implying that the high porosity is a diagenetic anomaly. Two possibilities exist to explain this anomaly. This localized porous zone may be attributed to a different burial or tectonic history relative to the rest of the Aklavik Formation outcrop. Or it may represent a localized area that was affected by an early cement, as suggested in section 4.3.2, which prevented later compaction and quartz cementation.

The effects of chemical compaction lessen, and therefore porosity generally increases, towards the eastern region of the study area. Assuming that chemical compaction is solely the result of burial and overburden pressure, it appears that rocks of the Aklavik Formation in outcrop were buried progressively deeper towards the west, due to their very low porosity values, corresponding to extensive cementation. However, it cannot be assumed that the Aklavik Formation in the

subsurface, which is situated farthest east and therefore assumed to have been exposed to the least amount of burial, corresponds to this trend. This observation is based on the first limitation previously mentioned, which stated subsurface rocks may have experienced different tectonic and burial histories than the equivalent outcrop exposures.

Tobin (1997) created a system for evaluating the degree of exploration risk from the study of outcrop samples, which is summarized in Figure 4.8. Using this flow chart, the two porosity trends identified in the outcrop of the Aklavik Formation were evaluated: the tightly cemented rocks characteristic of the western region are classified as Type 4, and the porous rocks of Martin Creek are considered to be Type 8. The risk assessment for Type 4 rocks is considered very high, unless factors such as rim cementation or dissolution occurred during diagenesis, which would then allow for the subsurface to have reservoir potential. Ramm *et al.* (1997) reported rim cementation hindered quartz precipitation and late diagenetic compaction in deep Upper Jurassic sandstones in the Norwegian Central Graben. However, the rim cement was identified as a microquartz coating, sourced from amorphous silica (volcanic glass and sponge spicules) during deposition. There was no evidence for silica of this type within samples of the Aklavik Formation, subsequently the presence of amorphous silica in the subsurface is considered very low. Isolated zones of dissolution are possible in the subsurface, as this trend was observed in outcrop, specifically the porous facies in the Martin Creek region. As already mentioned, it is speculated that in this region an early phase of cementation prevented the extensive later development of quartz cement that typically inhibits porosity in the rest of the study area. If circumstances allowed for this to occur in the Aklavik Formation in outcrop, than it is plausible that the same processes affected those sediments still in the subsurface. This scenario also addresses the risks associated with Type 8 rocks, which are considered to be moderate to high, unless similar dissolution or diagenetic traps can be predicted in the subsurface.

4.6 Summary

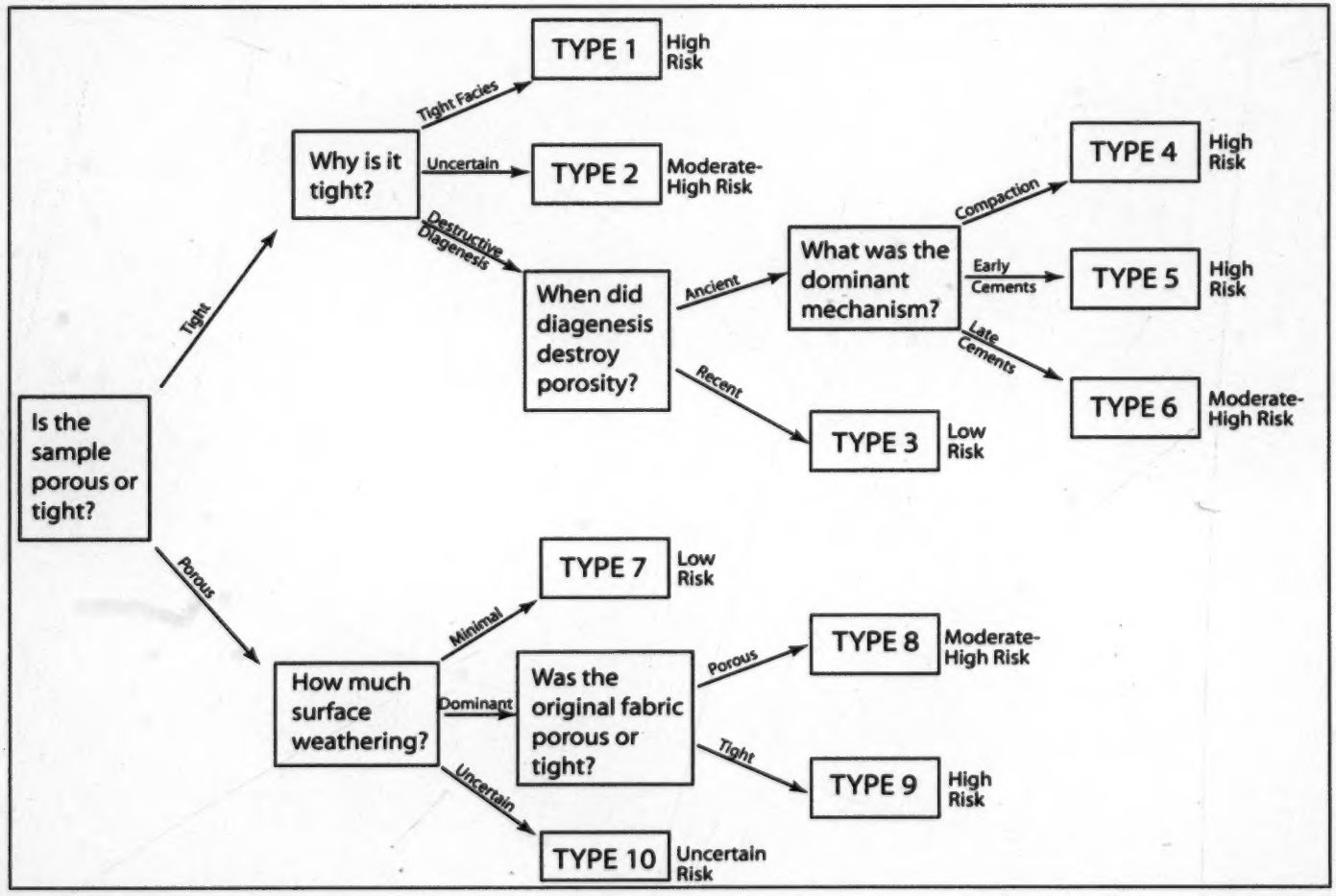
Rocks of the Aklavik Formation are classified as quartz arenitic to sublitharenitic. Only minor amounts of accessory components were identified, including chert, feldspar, kaolinite, metasedimentary rock fragments, various clays, chalcedony, rare heavy minerals, and micaceous flakes. Six different diagenetic phases were identified, which acted to enhance as well as destroy porosity. These processes include:

1. Mechanical compaction
2. Early cementation
3. Quartz overgrowth cementation and pressure solution
4. Dissolution and development of secondary porosity
5. Development of authigenic clays
6. Possible hydrocarbon migration

The Aklavik Formation consists of texturally mature quartz rich sandstones that reflect extensive reworking. Consequently, determining their direct provenance is very challenging. It can be assumed, though, that recycling from older formations contributed greatly.

Figure 4.8

Flow chart diagram modified from Tobin (1997). Used to evaluate the degree of exploration risk from the study of outcrop samples. Ten rock type categories are identified based on their potential as subsurface reservoir facies. The two porosity trends identified in the Aklavik Formation are classified as Type 4 and Type 8.


Is the sample porous or tight?
Tight
Porous
Why is it tight?
Tight Facies
Uncertain
Destructive Diagenesis
When did diagenesis destroy porosity?
Ancient
Recent
What was the dominant mechanism?
Compaction
Early Cements
Late Cements
TYPE 1
High Risk
TYPE 2
Moderate-High Risk
TYPE 3
Low Risk
TYPE 4
High Risk
TYPE 5
High Risk
TYPE 6
Moderate-High Risk
How much surface weathering?
Minimal
Dominant
Uncertain
Was the original fabric porous or tight?
Porous
Tight
TYPE 7
Low Risk
TYPE 8
Moderate-High Risk
TYPE 9
High Risk
TYPE 10
Uncertain Risk

Using outcrop data for predicting subsurface reservoir quality is generally less accurate than using data directly from the subsurface. However, in frontier basins such as the Brooks-Mackenzie Basin, sometimes outcrop samples are the best data set available. Overall, the sandstones of the Aklavik Formation are considered to be moderate to high risk reservoir targets, due to their extensive cementation and chemical compaction effects. However, detailed analysis of equivalent subsurface rocks may prove otherwise, due to differing burial and tectonic histories being possible for the subsurface and surface strata of the Aklavik Formation.

CHAPTER FIVE: CONCLUSIONS

This study of the Jurassic Aklavik Formation was undertaken in order to better understand the depositional environments that make up this unit, how the unit was deposited, and the unit's diagenetic history.

Within the study area, twelve facies were identified from the Aklavik Formation, as well as parts of the underlying Richardson Mountains Formation and overlying Husky Formation. Facies A through H were interpreted to represent progradation of a high-energy, wave-dominated delta and associated strandplains. The basin at the time of deposition of the Aklavik Formation was exposed to frequent storm events that typically eroded any fair-weather deposits that may have developed, as well as continually provided challenging environments for organisms to adapt to. This facies package, or association, represents regressive conditions during a highstand systems tract (HST). Fluctuations within this association, which may appear as sea-level changes, were due to local variances attributed to autocyclic changes to the deltaic system. The facies associated with this highstand are the most common and most typical of the Aklavik Formation.

Facies I through L are interpreted as various environments associated with progressively deepening water. This facies package represents deposition under transgressive conditions, and is therefore part of the transgressive systems tract (TST). During this time, the Aklavik delta ceased to prograde, due to sedimentation rates not being able to keep up with the creation of accommodation space. Additionally, the upper portions of the well-developed shorefaces, characteristic of the Aklavik Formation, were reworked and modified into transgressive depositional environments. These are speculated to include a barrier island system that was progressively flooded to allow for shelf sediments, represented by Facies L of the Husky Formation, to be deposited in the vicinity of the previously existing Aklavik shoreline.

The ichnology that was documented in this study proved to be a useful tool, and completed the picture of the conditions during deposition of the Aklavik Formation. Elements of both the *Cruziana* and *Skolithos* ichnofacies were identified, although they were not always associated with the shoreface environments that they have come to typify. For example, the *Cruziana* ichnofacies was characterized by more vertical to subvertical components, and therefore classified as a proximal *Cruziana* assemblage. This lack of fully horizontal forms reflects the adaptable behaviour of the organisms to the continuously high wave energy that defined the system. The ichnology of the Aklavik Formation demonstrated that these ichnofacies are not always found in the shoreface environments that they are commonly expected in.

A *Glossifungites* assemblage was also identified, locally marking the tops of certain outcrops. This assemblage was classified as a *Glossifungites* suite based on the dense community of dwelling traces and the preserved imprints of woody material, suggesting that the substrate was relatively cohesive at the time of colonization. However, this surface is not considered to be temporally significant, and is better described as a depositional hiatus.

Sequence stratigraphic surfaces were identified near the top of the Aklavik Formation, and were observed in outcrop as well as depicted in the included cross-section for this thesis. The surface

of initial transgression (IT) marks the change from highstand to transgressive systems tract. A transgressive surface of erosion (TSE) was also identified, represented by the *Glossifungites* assemblage that was observed locally. These surfaces aided in the interpretation of depositional environments and basinal conditions such as sea level positioning. Nevertheless, it was noted that these transgressive surfaces, especially the TSE, can be highly diachronous, and should therefore not be relied upon for regional correlations. The shift from HST to TST was the result of basin subsidence, possibly activated by the extensional tectonic regime during that time.

Sandstones of the Aklavik Formation were identified petrologically as consisting of quartz arenites to sublitharenites. A generalized diagenetic sequence was outlined, including six different processes. These include:

- Mechanical compaction
- Early cementation
- Quartz overgrowth cementation and pressure solution
- Dissolution and development of secondary porosity
- Development of authigenic clay
- Possible hydrocarbon migration

Well-sorted, rounded, monocrystalline quartz grains, indicating the very mature nature of the sands, as well as supporting a history of extensive reworking, dominated the sandstone of the Aklavik Formation. These sandstones are interpreted to have been derived from the south and southeast. This suggests a cratonic source, as well as being derived from clastic units from the Paleozoic. This agrees with previous work by Young (1973) and Poulton *et al.* (1982).

Mesozoic rocks of the Mackenzie Delta are of significant interest to geologists, especially in relation to petroleum companies who explore in the onshore regions of the delta. This study, including careful descriptions and interpretations of the Aklavik Formation, as well as outlined diagenetic processes affecting this unit, may assist with and facilitate future drilling of economically viable reservoirs in the area.

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APPENDIX I
Measured Sections and Photo Mosaics

Appendix I contains drafted lithologs for fifteen of the sixteen sections that were measured during the 2001 field season. Their locations are shown on a map in Figure 1.2 (Chapter 1). Where available, photo mozaics are included after each of the lithologs. Each section name, location (given in Latitude and Longitude), and interval measured are stated at the top of each litholog. Note that not all sections are from the Aklavik Formation. Below is a legend of all symbols used on the lithologs.

Litholog Legend

Ichnofossil Symbols

Arenicolites (Ar)	*Asterosoma (As)*	*Chondrites (Ch)*
Cylindrichnus (Cy)	*Diplocraterion (Di)*	*Fugichnia (Fu)*
Polykladichnus (Po)	*Ophiomorpha (Op)*	*Palaeophycus (Pa)*
Planolites (Pl)	*Rosselia*	*Skolithos (Sk)*
Teichichnus (Te)	*Thalassinoides (Th)*	Undifferentiated burrow

Physical Sedimentary Structures

Wavy bedding (heterolithic)	Planar cross-stratification
Wavy bedding (homogeneous)	Trough cross-stratification
Ripple laminations (wave)	Planar bedding
Low angle cross-stratification	Swaley cross-stratification
Hummocky cross-stratification	Sigmoidal cross-stratification

Contacts

Gradational — Scoured/Storm event — Sharp

Extras

Carbonaceous matter	Stylolite	Photo available
Carbonaceous laminae	Siderite	Sample collected
Glossifungites surface	Wood lag	Graded bedding
Wood debris	Pebble stringer	

Lithology

Sandstone — Siltstone — Shale

Trough cross-bedded sandstone — Sandstone with mudtone laminae

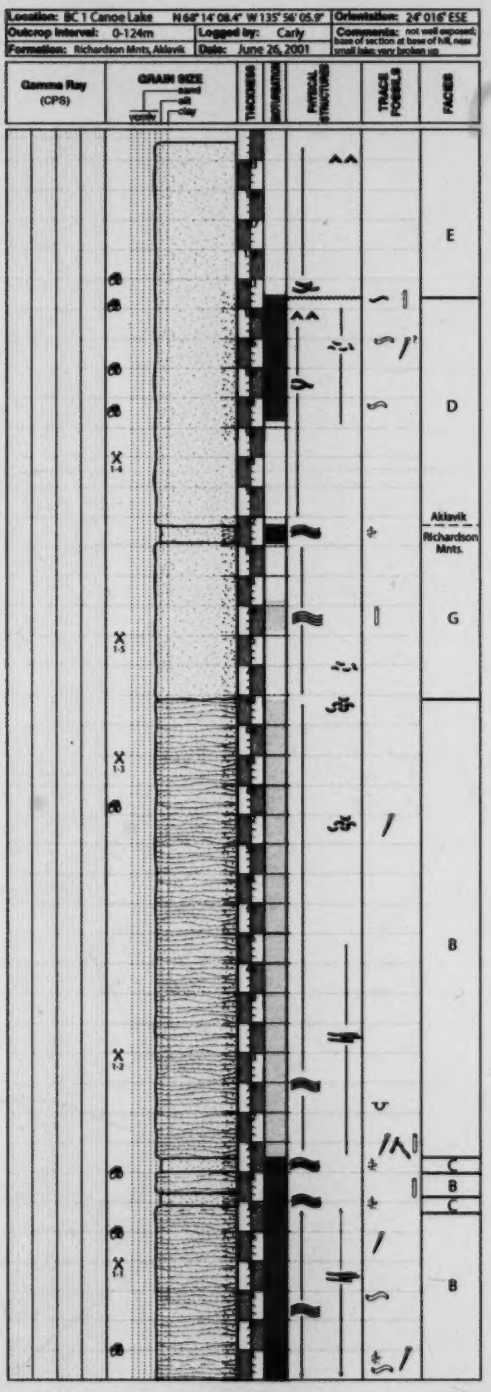

Location: BC 1 Canoe Lake N 68° 14' 08.4" W 135° 56' 05.9"
Orientation: 24° 016° ESE
Outcrop Interval: 0-124m
Logged by: Carly
Comments: not well exposed, base of section at base of hill, near small lake, very broken up
Formation: Richardson Mnts, Aklavik
Date: June 26, 2001
Gamma Ray (CPS)
GRAIN SIZE
sand
silt
clay
gravel
THICKNESS
LAMINATION
PHYSICAL STRUCTURES
TRACE FOSSILS
FACIES
E
D
Aklavik
Richardson Mnts.
G
B
B
B
X4
X3
X2
X1

Photo mosaic of Section 1 from Canoe Lake

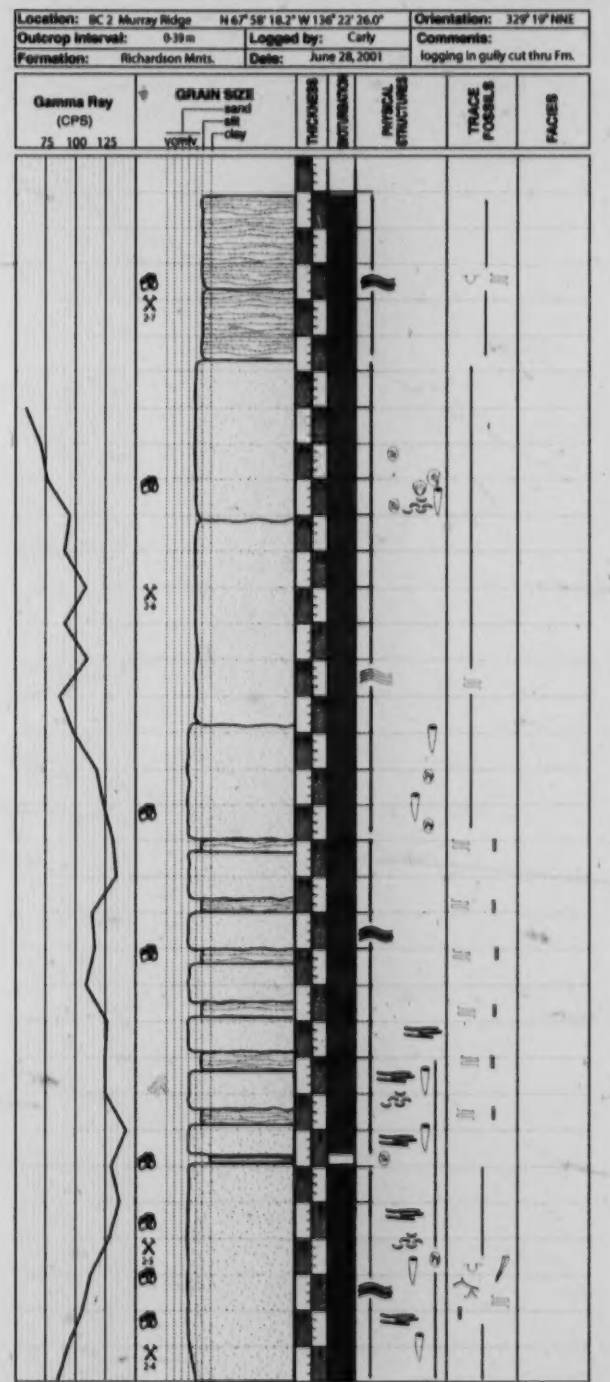
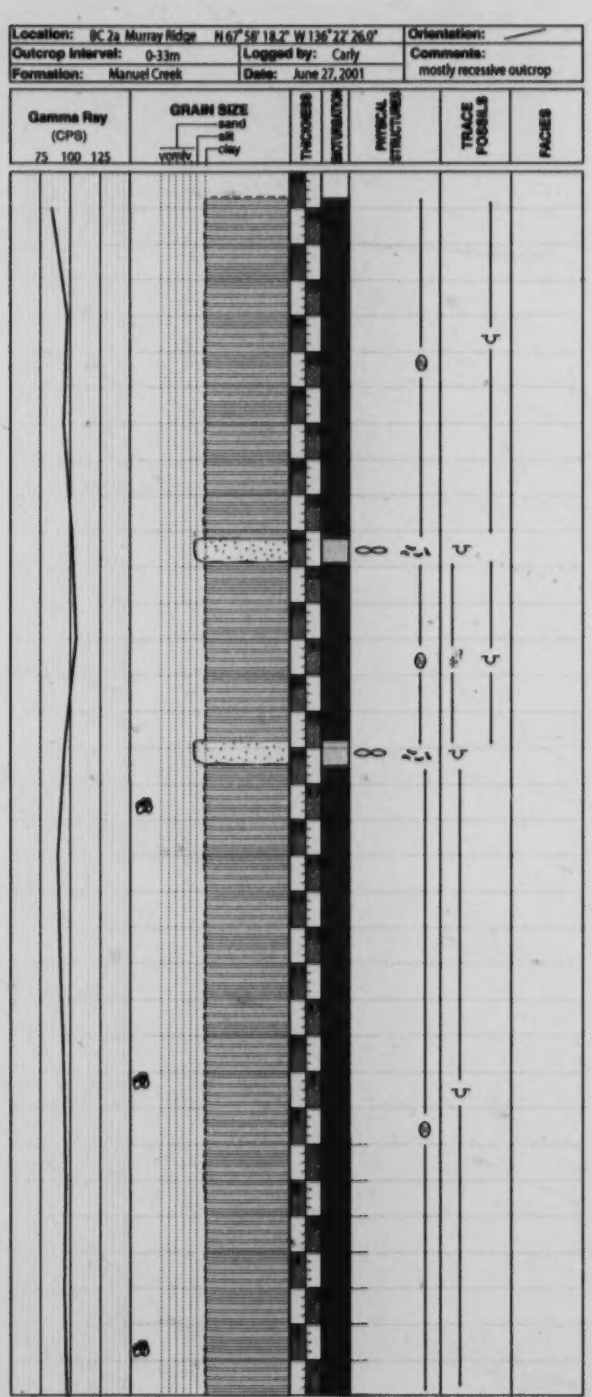

Location: BC 2 Murray Ridge N 67° 58' 18.2" W 136° 22' 26.0"
Orientation: 329° 19° NNE
Outcrop interval: 0-39 m
Logged by: Carly
Comments:
Formation: Richardson Mnts.
Date: June 28, 2001
logging in gully cut thru Fm.
Gamma Ray (CPS)
75 100 125
GRAIN SIZE
sand
silt
clay
vcmfv
THICKNESS
BIOTURBATION
PHYSICAL STRUCTURES
TRACE FOSSILS
FACIES

Photo mosaic of Section 2, Murray Ridge


Location: BC 2a Murray Ridge N 67° 58' 18.2" W 136° 22' 26.0"
Orientation:
Outcrop interval: 0-33m
Logged by: Carly
Comments:
mostly recessive outcrop
Formation: Manuel Creek
Date: June 27, 2001
Gamma Ray
(CPS)
75 100 125
GRAIN SIZE
sand
silt
clay
vcmfc
THICKNESS
BIOTURBATION
PHYSICAL STRUCTURES
TRACE FOSSILS
FACIES

Location: BC 4 Martin Creek	N 68° 09' 59.6" W 135° 44' 27.0"		**Orientation:** 170° 22° W
Outcrop Interval: 0-15m	**Logged by:** Carly		**Comments:** SW side of creek
Formation: Aklavik	**Date:** June 29, 2001		

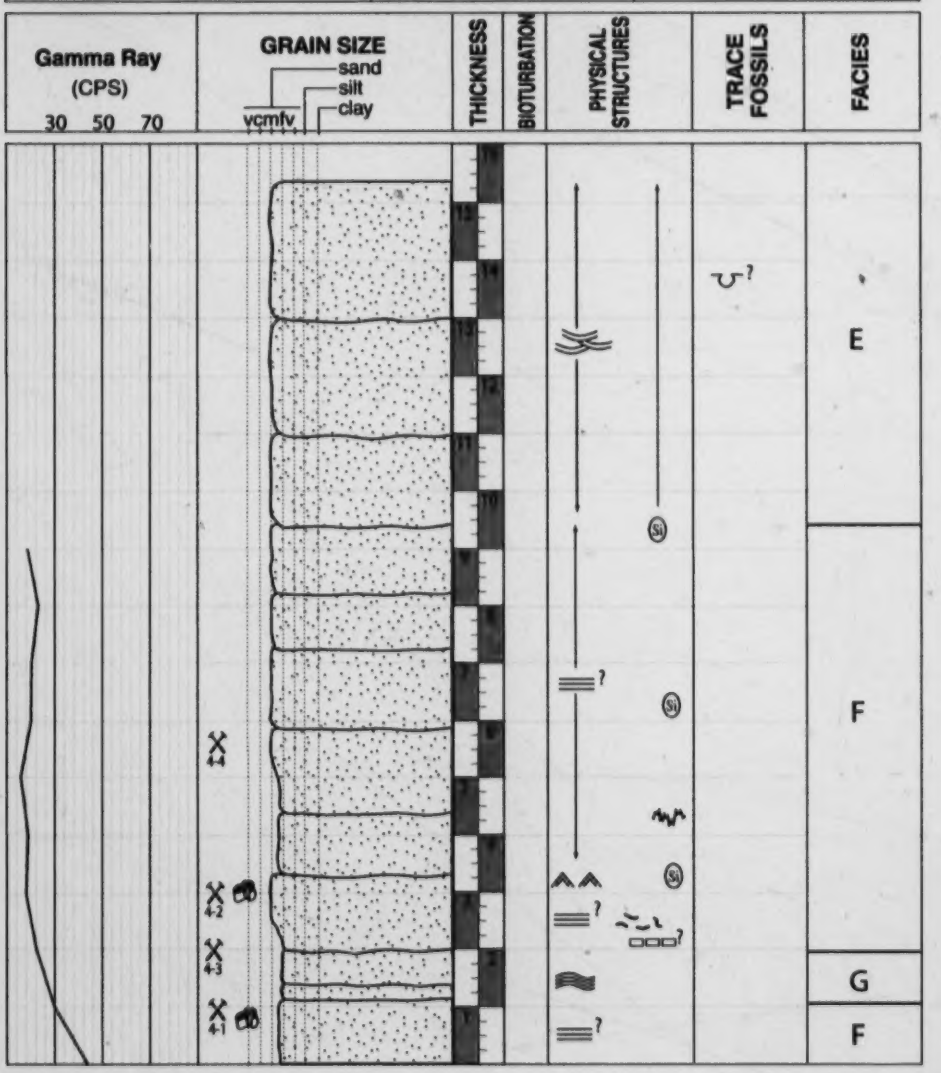
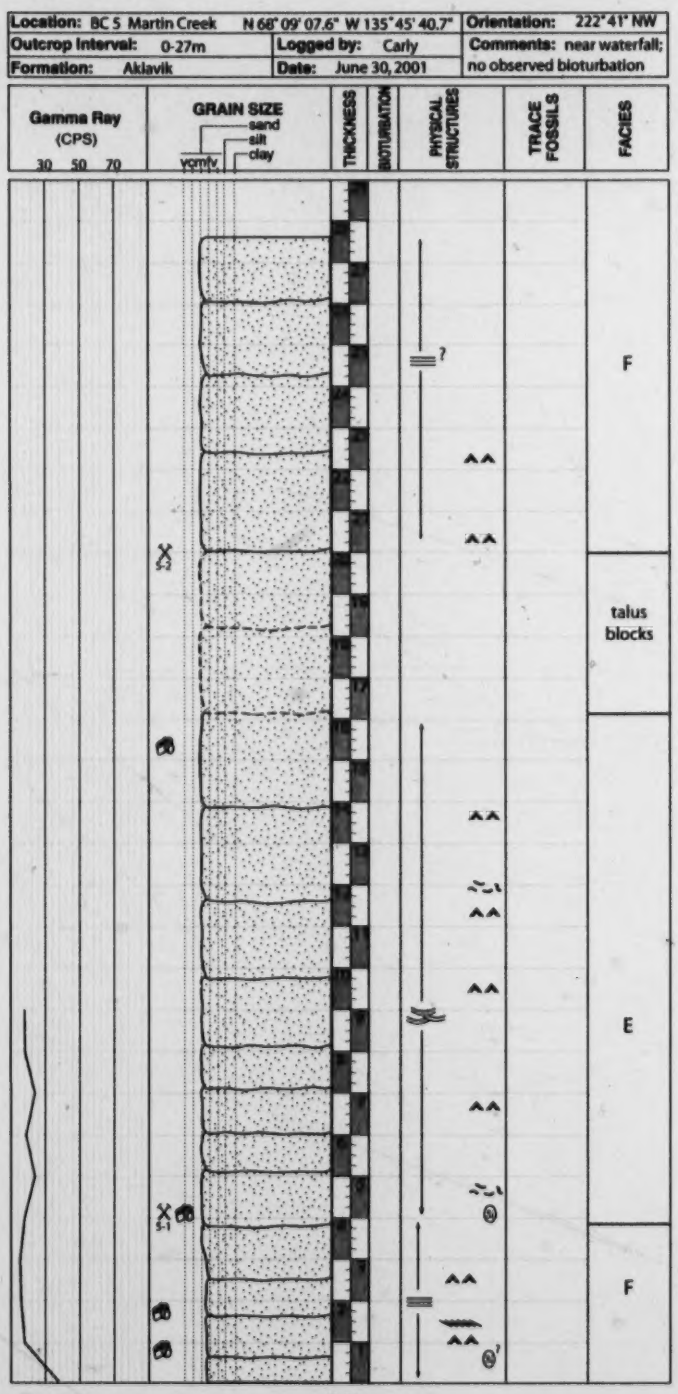


Photo mosaic of Section 4, Martin Creek


Location: BC 5 Martin Creek N 68° 09' 07.6" W 135° 45' 40.7"
Orientation: 222° 41° NW
Outcrop Interval: 0-27m
Logged by: Carly
Comments: near waterfall; no observed bioturbation
Formation: Aklavik
Date: June 30, 2001
Gamma Ray (CPS)
30 50 70
GRAIN SIZE
sand
silt
clay
vc m f v
THICKNESS
BIOTURBATION
PHYSICAL STRUCTURES
TRACE FOSSILS
FACIES
F
talus blocks
E
F
S2
S1

Location: BC 6 Upper Murray Ridge N 67° 58' 29.2" W 136° 21' 25.9"		**Orientation:** 320°20°NNE
Outcrop Interval: 0-10.5m	**Logged by:** Carly	**Comments:** not able to get to to true base of Aklavik (~30m true thickness)
Formation: Aklavik	**Date:** July 1, 2001	

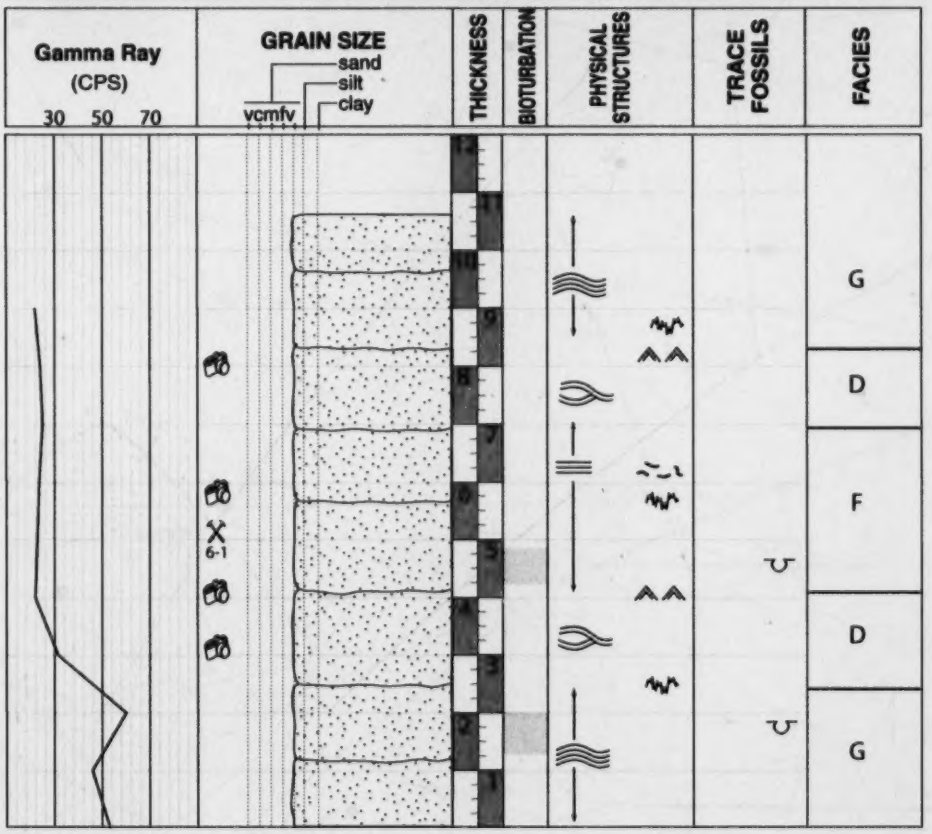


Photo mosaic of Section 6, Upper Murray Ridge

Location:	BC 7 Martin Creek	N 68° 09' 07.7" W 135° 42' 48.7"	Orientation:	135°09'SW
Outcrop Interval:	0-23.75m	Logged by:	Carly	Comments:
Formation:	Aklavik	Date:	July 4, 2001	

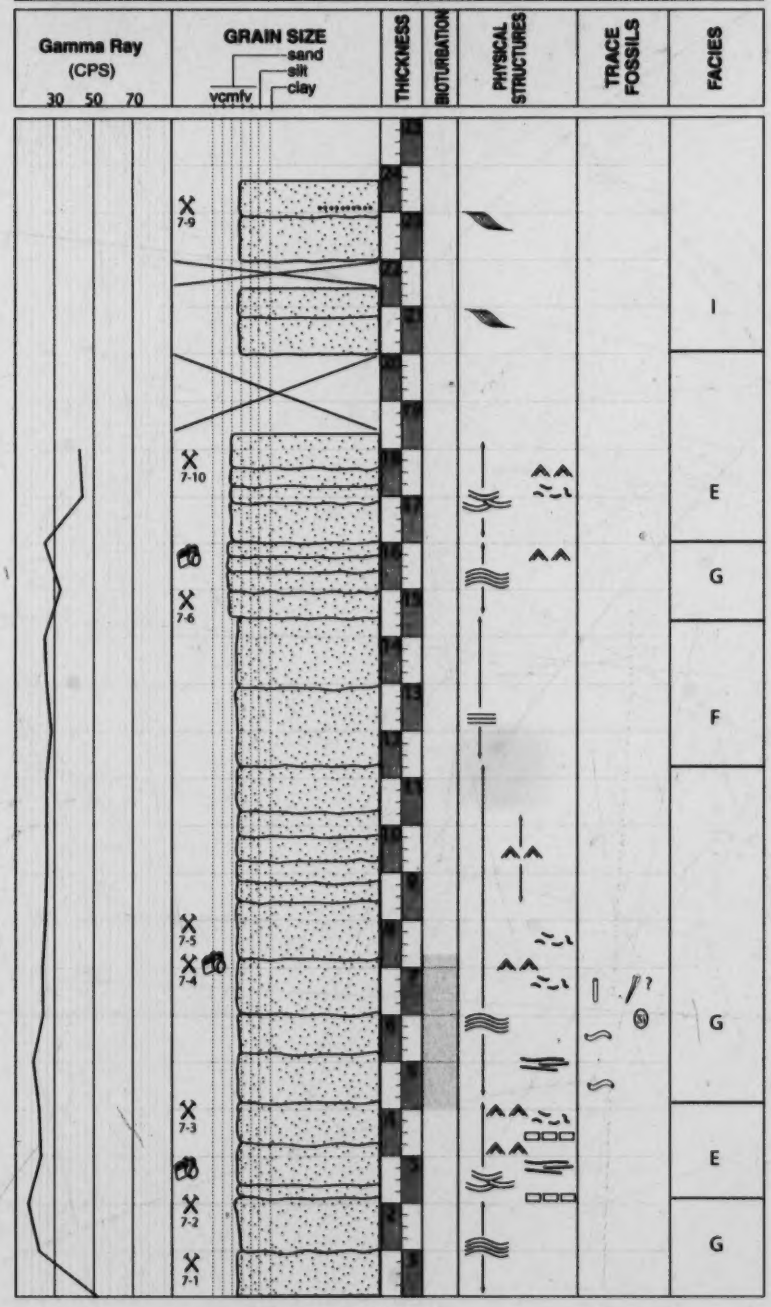
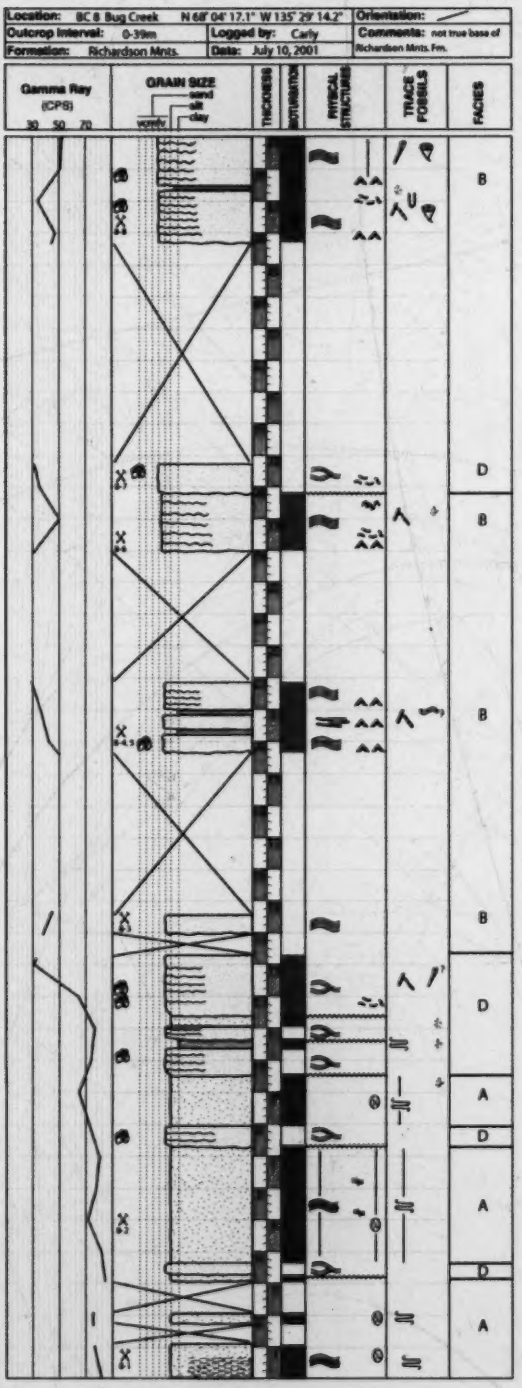


Photo mosaic of similar outcrop across creek from Section 7, Martin Creek


Location: BC 8 Bug Creek N 68° 04' 17.1" W 135° 29' 14.2"
Orientation:
Outcrop Interval: 0-39m
Logged by: Carly
Comments: not true base of Richardson Mnts. Fm.
Formation: Richardson Mnts.
Date: July 10, 2001
Gamma Ray (CPS)
30 50 70
GRAIN SIZE
sand
silt
clay
vc m f
THICKNESS
BIOTURBATION
PHYSICAL STRUCTURES
TRACE FOSSILS
FACIES
B
D
B
B
B
D
A
D
A
D
A

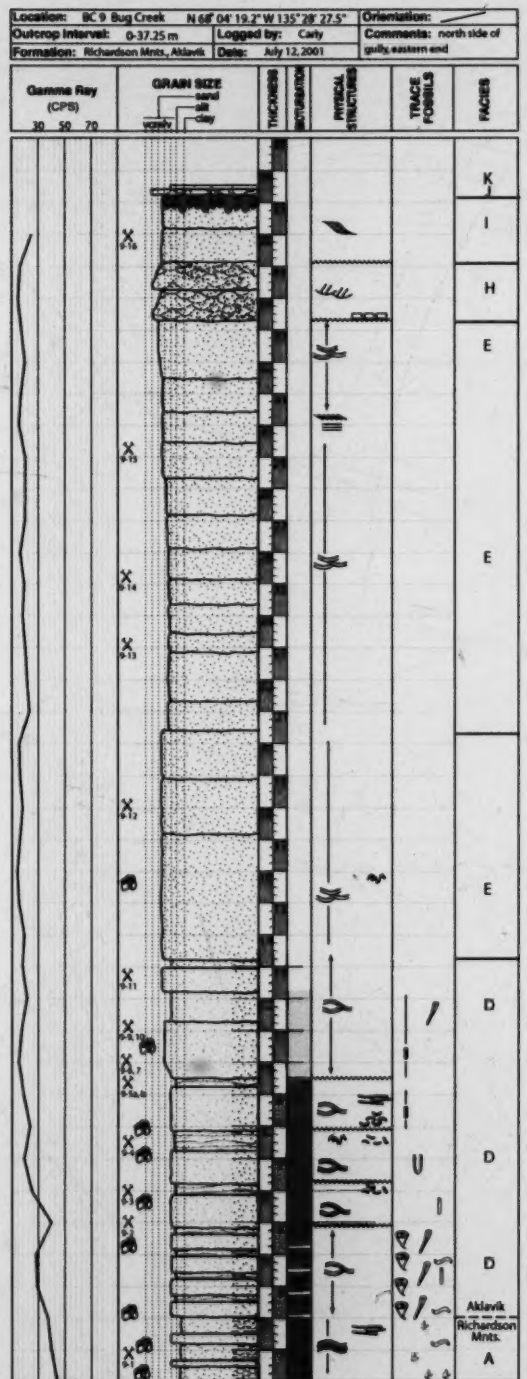
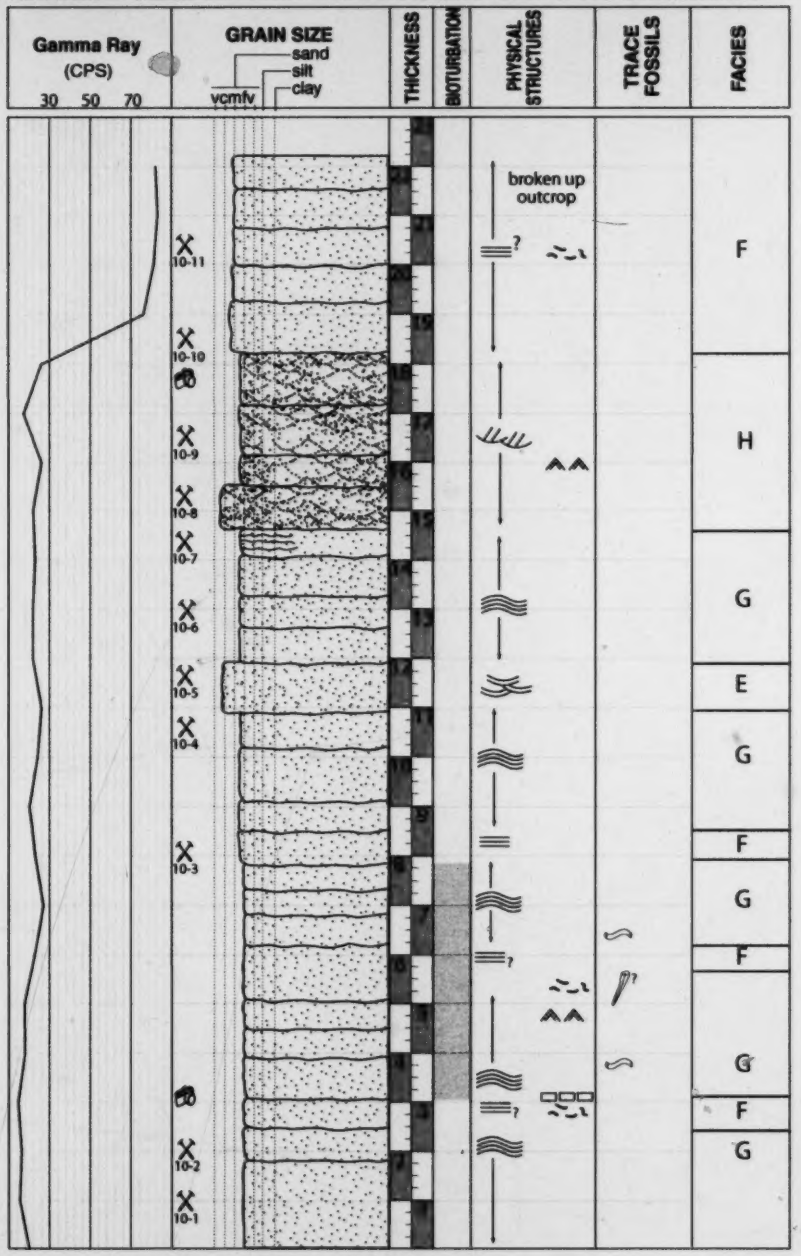

Location: BC 9 Bug Creek N 68° 04' 19.2" W 135° 28' 27.5"
Orientation:
Outcrop Interval: 0-37.25 m
Logged by: Carly
Comments: north side of gully, eastern end
Formation: Richardson Mnts., Aklavik
Date: July 12, 2001
Gamma Ray (CPS)
30 50 70
GRAIN SIZE
sand
silt
clay
vc vf
THICKNESS
BIOTURBATION
PHYSICAL STRUCTURES
TRACE FOSSILS
FACIES
K
I
H
E
E
E
D
D
D
Aklavik
Richardson Mnts.
A

Photo mosaic of location of Sections 8 and 9, Bug Creek Canyon

Location: BC 10 Martin Creek N 68° 10' 57.4" W135° 40' 13.5"			**Orientation:**
Outcrop Interval: 0-22.25 m	**Logged by:** Carly		**Comments:** section near slump zone; very broken up outcrop
Formation: Aklavik	**Date:** July 13, 2001		



* Upper 3m of GR log influenced by overburden

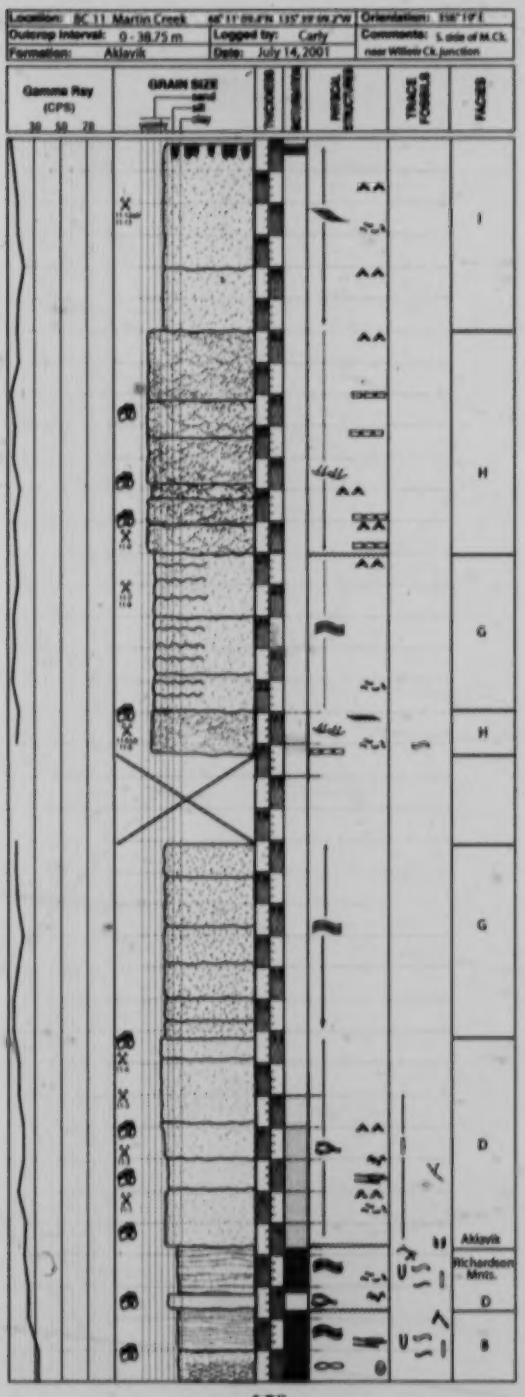
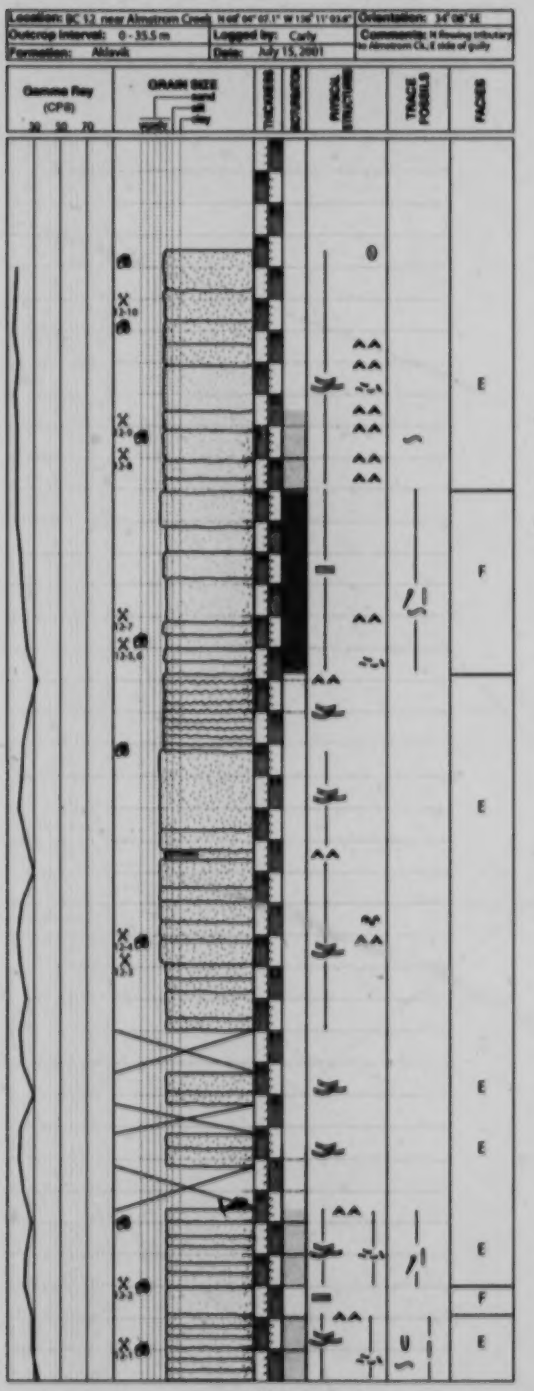

Location: BC 11 Martin Creek
Orientation:
Outcrop Interval: 0 - 38.75 m
Logged by: Carly
Comments: S. side of M.Ck. near Wilson Ck. junction
Formation: Aklavik
Date: July 14, 2001
Gamma Ray (CPS)
30 50 70
GRAIN SIZE
sand
silt
clay
weathering
TRACE FOSSILS
FACIES
I
H
G
H
G
D
Aklavik
Richardson Mnts.
D
B

Photo mosaic of Martin Creek region, with Sections 10 and 11 highlighted


Location: BC 12 near Almstrom Creek, N of 56° 07.1' W 136° 11' 03.6"
Orientation: 34° 08' SE
Outcrop Interval: 0 - 35.5 m
Logged by: Carly
Comments: N flowing tributary to Almstrom Ck, E side of gully
Formation: Aklavik
Date: July 15, 2001
Gamma Ray (CPS)
30 50 70
GRAIN SIZE
sand
silt
clay
vf m c
THICKNESS
BOUNDARY
PHYSICAL STRUCTURES
TRACE FOSSILS
FACIES
E
F
E
E
E
E
F
E

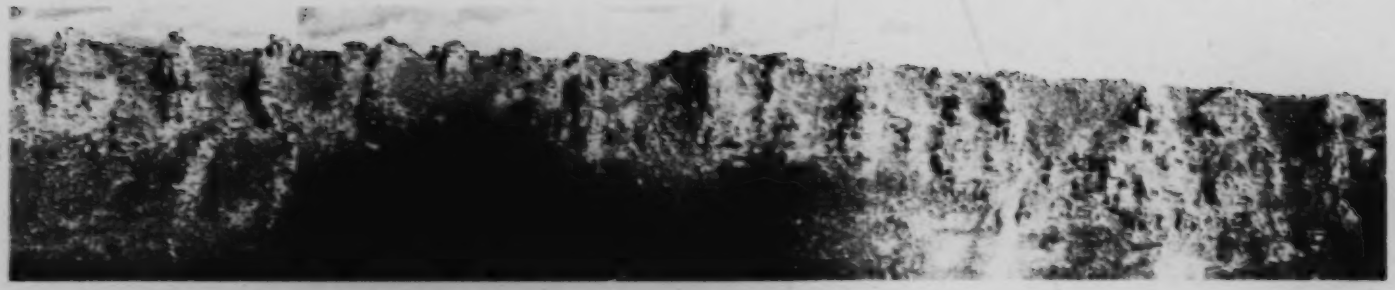
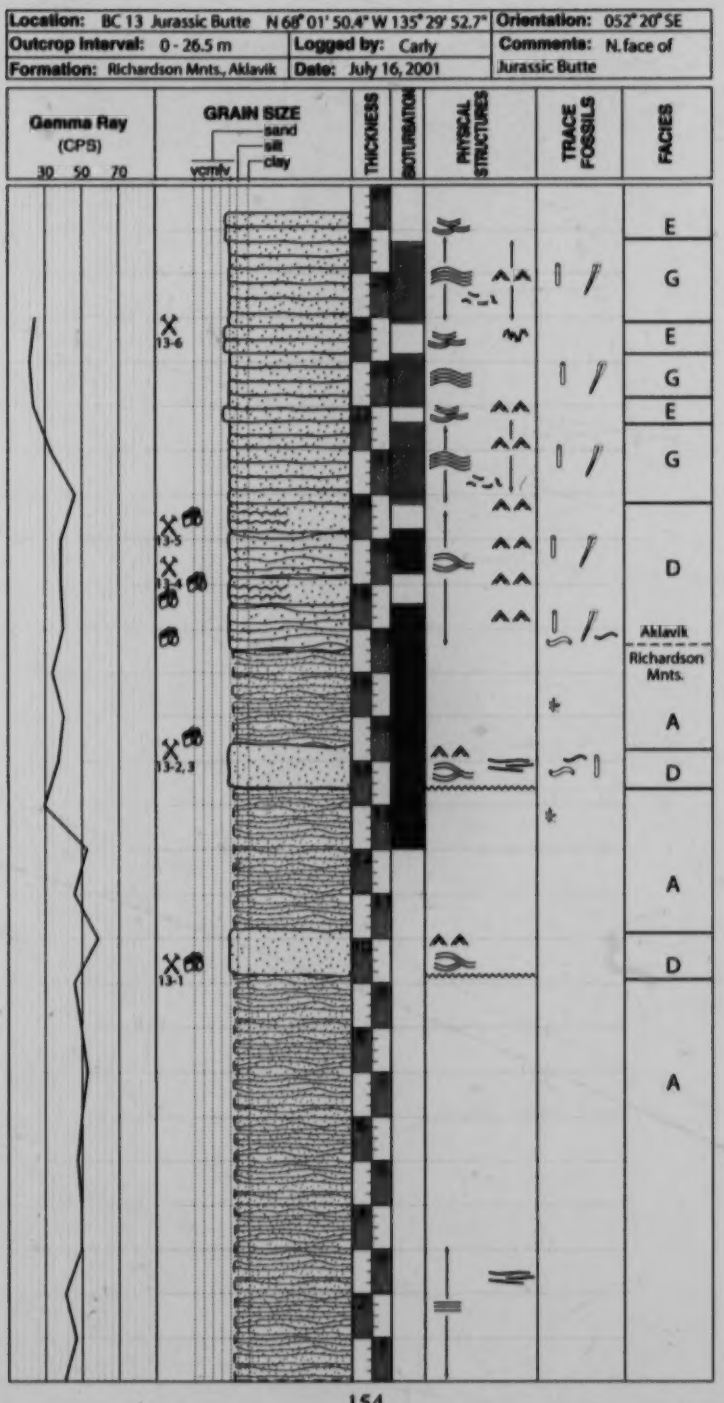
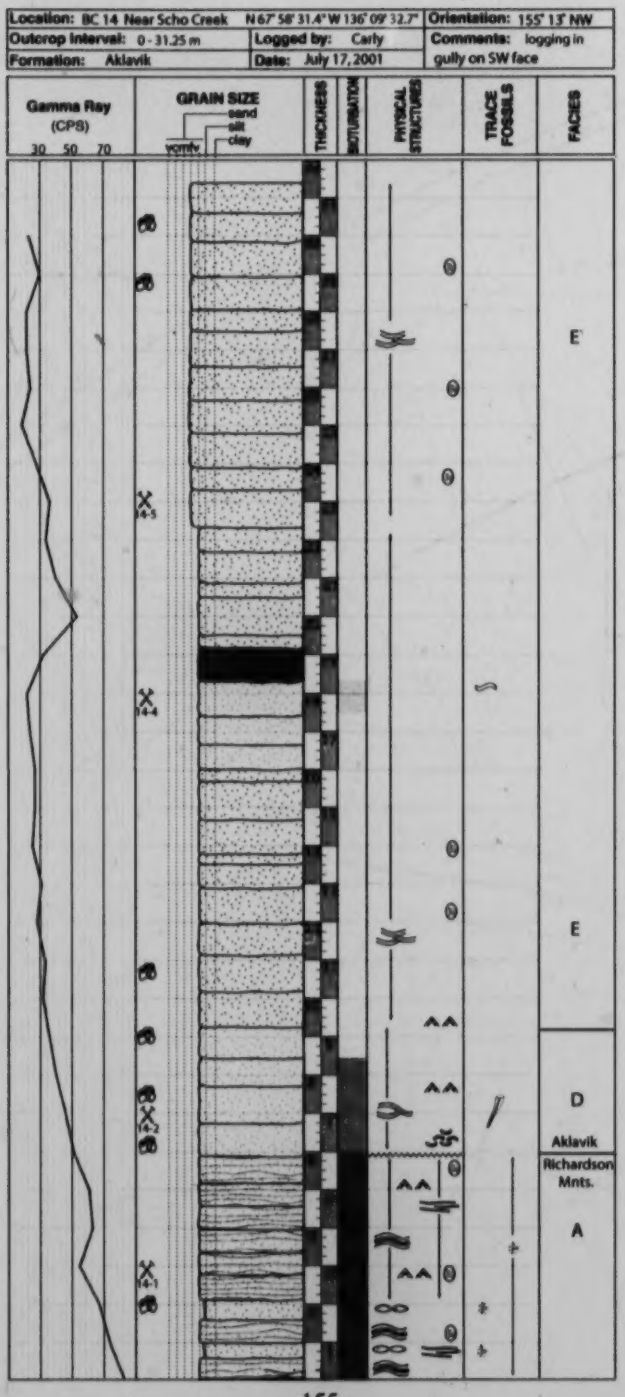


Photo mosaic of Section 12, near Almstrom Creek


Location: BC 13 Jurassic Butte N 68° 01' 50.4" W 135° 29' 52.7"
Orientation: 052° 20° SE
Outcrop interval: 0 - 26.5 m
Logged by: Carly
Comments: N. face of Jurassic Butte
Formation: Richardson Mnts., Aklavik
Date: July 16, 2001
Gamma Ray (CPS)
30 50 70
GRAIN SIZE
sand
silt
clay
vc m f v
THICKNESS
BIOTURBATION
PHYSICAL STRUCTURES
TRACE FOSSILS
FACIES
13-6
13-5
13-4
13-2, 3
13-1
E
G
E
G
E
G
D
Aklavik
Richardson Mnts.
A
D
A
D
A


Location: BC 14 Near Scho Creek N 67° 58' 31.4" W 136° 09' 32.7"
Outcrop interval: 0 - 31.25 m
Formation: Aklavik
Logged by: Carly
Date: July 17, 2001
Orientation: 155° 13° NW
Comments: logging in gully on SW face
Gamma Ray (CPS)
30 50 70
GRAIN SIZE
sand
silt
clay
vcmfv
THICKNESS
BIOTURBATION
PHYSICAL STRUCTURES
TRACE FOSSILS
FACIES
14-5
14-4
14-2
14-1
E
E
D
Aklavik
Richardson Mnts.
A

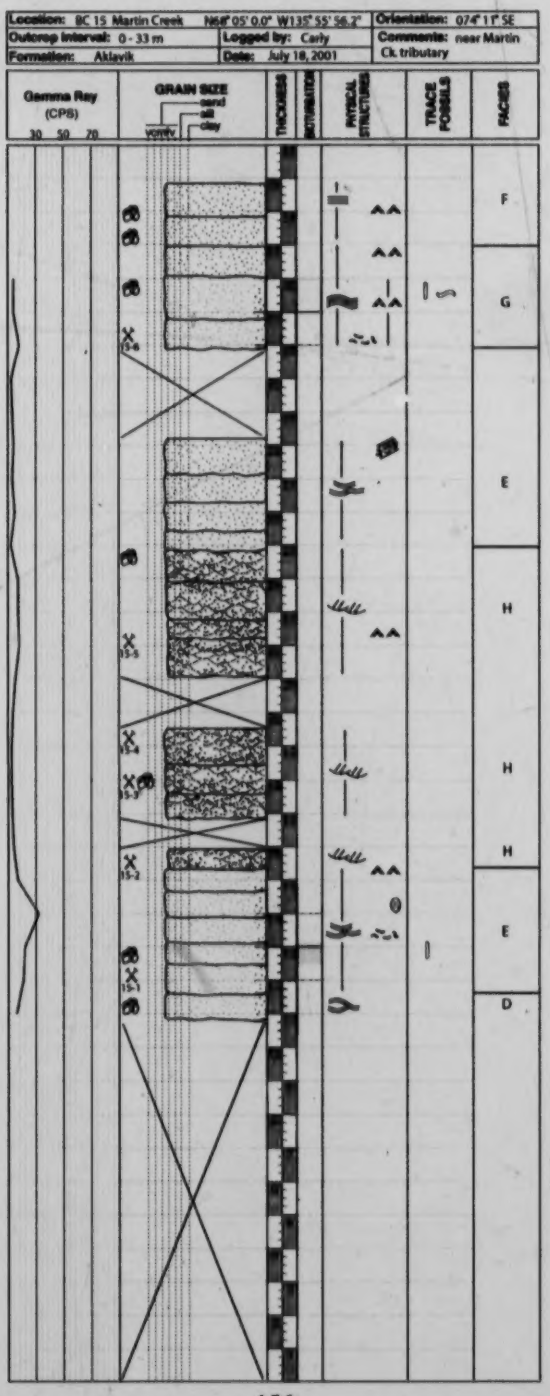

Location: BC 15 Martin Creek N68° 05' 0.0" W135° 55' 56.7"
Orientation: 074° 11° SE
Outcrop Interval: 0 - 33 m
Logged by: Carly
Comments: near Martin Ck. tributary
Formation: Aklavik
Date: July 18, 2001
Gamma Ray (CPS)
30 50 70
GRAIN SIZE
sand
silt
clay
vcmfv
THICKNESS
BIOTURBATION
PHYSICAL STRUCTURES
TRACE FOSSILS
FACIES
F
G
E
H
H
H
E
D

Photo mosaic of Section 15, southwestern end of Martin Creek

APPENDIX II
Thin Section Descriptions

RE-MAC-AK1

Cement
- silica

Mineralogy
- quartz rich
- relatively higher chert content; altered chalcedony
- mud clasts
- rare heavy minerals – spinel, zircon
- localized barite (?) crystals

Texture
- poorly sorted – inter-granular porosity
- subrounded
- few large clasts – comprised of chert, mud
- good porosity – some sutured grains
- some grains leached/altered

Comments
- organics present
- odd, elongate, slat-like crystals
    - randomly arranged, cemented together
- sample from the lag deposit
- sublitharenite rock

RE-MAC-AK2

Comments
- very similar to Ak1
- both samples from lag deposit
- pebble size meta-sedimentary clasts (quartzite pebble)

RE-MAC-AK3

Cement
- overall quartz cement
- only few pore spaces suggest possible carbonate (calcite) cement, because of sharp quartz edges

Mineralogy
- chert, few chalcedony crystals
- few polycrystalline quartz crystals
- rare heavy minerals – zircon
- dominantly monocrystalline quartz grains

Texture
- secondary porosity – due to leaching of quartz grains
- leached quartz grains
- mostly inter-granular porosity
- moderate sorting
- rounded to subrounded

Comments
- few possible organics rimming some grains
- not a lot of obvious quartz dissolution along grain contacts
- few obvious quartz overgrowths

RE-MAC-AK4

Cement
- dominantly quartz cement
  - thin layer of cement
- possible remnant calcite cement – probably fully leached
  - speculated from the angular quartz grains
  - or possibly just small quartz overgrowths

Mineralogy
- dominantly monocrystalline quartz
- rare polycrystalline crystals
- few chert grains
  - larger amount of chert relative to AK3
- rare clay minerals – very fine grained

Texture
- inter-granular porosity dominant
  - more common relative to AK3
- overall moderately sorted
  - grains are mostly similar size, with few larger grains mixed in (slightly bimodal)
  - equant and oblong grains
- quartz grains commonly have jagged edges – evidence for a carbonate cement that has not been leached away

Comments
- mud linings around some grains
  - possible iron staining or limonite?
- few grains welded together, but not common
  - fewer compared to AK3
- good porosity and conductivity of pores
  - porosity estimated between 10 and 14%
- appears to be less compaction and silica cementing than other samples
- compaction has only slightly affected this sample

RE-MAC-AK5a

Cement
- silica

Mineralogy
- dominantly monocrystalline quartz
- rare heavy minerals – spinel, zircon
- few cherts
  - relatively more compared to AK3 and AK4

Texture
- higher degree of welded grains than AK3, AK4

Comments
- shear zone – late feature, probably not the source for quartz since there does not appear to be more quartz cementing closer to the shear zone

RE-MAC-AK5b

Cement
- same as 5a

Mineralogy
- same as 5a

Texture
- secondary porosity created by leaching of a few quartz grains

Comments
- thin section taken from same rock sample as AK5a

RE-MAK-AK6

Cement
- all silica cement
  - thin layer coating grains
- jagged edges of quartz grains suggests early phase of carbonate cement

Mineralogy
- mostly monocrystalline grains
- few polycrystalline
- chert, chalcedony, rare kaolinite
- one zircon crystal

Texture
- some grains welded together
- rare quartz overgrowths
- moderately to poorly sorted – considered bimodal
  - smaller grains are more equant than the larger grains
  - grains are more rounded than AK4 sample = more mature

Comments
- random large quartz grains (rare) with inclusions of heavy minerals (zircon, apatite?)
- bimodal nature restricts pore throats slightly – therefore less permeability that well sorted samples
- porosity effected mostly by compaction and sorting (bimodal)

RE-MAC-AK7

Cement
- silica

Mineralogy
- dominantly monocrystalline
- few polycrystalline grains – altered appearance
- kaolinite
  - infilling a few pore spaces
- chert and chalcedony
- rare heavy minerals – zircon, tourmaline
  - by far the most relative to AK3,4,5,6

Texture
- grains appear "glued" together rather than welded
- few leached grains
  - creating intra-granular porosity in less stable silicate minerals (ie: chert, chalcedony)
- few quartz overgrowths
- porosity inhibited by little kaolinite occluding pore spaces, but more affected by compaction

Comments

RE-MAC-AK8

Cement
- silica

Mineralogy
- dominantly monocrystalline quartz
- rare heavy minerals – tourmaline
- little chert

Texture
- relatively less pore space (compared to channel facies)
- moderately to well sorted
  - this facies (swaley) shows better sorting than channel facies
  - this suggests hydraulic influence creating better sorted rocks
- finer grained than channel facies
  - most grains are equant

Comments
- porosity reduced by compaction, but the conductivity is still okay
- generally appears to be more heavy minerals and less stable silicate minerals than the channel facies
- some type of opaque staining
  - pyrite or bitumen
- only a few occurrences of kaolinite

- cloudy quartz grains are common
    - a result of fluid inclusions
    - appear to be aligned – suggesting a stress regime (but most likely a protolith feature)

RE-MAC-AK9

Cement
- silica
- greater amount of cement relative to AK8
    - this decreases porosity and permeability relative to AK8

Mineralogy
- dominantly monocrystalline
- relatively more polycrystalline quartz crystals relative to other previous samples
- kaolinite present
    - infilling pore spaces
- partially leached feldspars
    - the feldspar grains are typically a slightly finer grain size than the quartz grains

Texture
- little porosity – grains very close together
    - porosity is generally inter-granular, but also some intra-granular because of dissolved grains
- subrounded grains
    - not as well rounded as the channel facies
    - equant grains
- moderately well to well sorted

Comments
- like AK8, this sample is from the swaley facies as well
    - but there appears to be more altered silicates – resulting in cloudy/brown grains under plain light

RE-MAC-AK10

Cement
- silica

Mineralogy
- monocrystalline quartz
- few cherts
- rare heavy minerals
- one grain (pellet) of glauconite
- partially dissolved feldspars
    - show a perthitic texture
- rare rock fragments (metasedimentary)
- possible mica flakes - biotite

Texture

- inter-granular and some intra-granular pores from leaching of less stable grains
- appears to be more organics
- overall texture appears to be similar to AK9
- limited pore space
    - inter-granular porosity effected by compaction

Comments

RE-MAC-AK11

Cement

- silica

Mineralogy

- monocrystalline quartz
- chert
- "dirty" quartz – altered rock fragments
- dissolved feldspars
    - perthitic texture
- rare glauconite
- rare mica flakes

Texture

- less porosity
    - well cemented – few inter-granular pores
- pore spaces are larger than grains – due to plucking during thin section preparation
- many grains welded together
- well sorted
- subrounded – equant grains

Comments

- higher amount of organics (relative to other samples)
    - present in laminae and inter-granular pores
    - some type of bitumen stain (?)
- this sample is from the Richardson Mountains Formation
    - there appears to be an increase in glauconite and feldspar moving downwards in section
- sublitharenite
- porosity is created by the dissolution of feldspar grains and less stable silicate minerals

RE-MAC-AK12

Cement

- silica
- possible clay linings acting as cement

Mineralogy
- monocrystalline quartz
- chert
- "dirty" quartz – altered
  - probably meta-sedimentary rock fragments
- few glauconite grains
- feldspar – more common than other samples
- few heavy minerals

Texture
- generally poor porosity
- well sorted
- quartz grains appear somewhat more angular

Comments
- high organic content – banded
- sample taken from *Chondrites* facies
  - can see a wall of organics around zone with no organics = burrow
- dissolution of the feldspar grains creates very rare open pores (ie: <5%)
  - poor conductivity

RE-MAC-AK13a

Cement
- silica
- possible earlier phase of carbonate cement (calcite), but now fully leached away
  - evidence is small scale irregular quartz crystal boundaries

Mineralogy
- monocrystalline quartz
- rare chert
- rare heavy minerals – zircon, rutile
- very little organics

Texture
- well rounded – subrounded grains
- generally good porosity

Comments
- from distributary channel facies

RE-MAC-AK13b

Cement
- silica

Mineralogy
- monocrystalline quartz
- few chert

- rare zircon

Texture
- subrounded
- well sorted
- generally okay porosity

Comments
- no organics

RE-MAC-AK14

Cement
- silica

Mineralogy
- monocrystalline quartz
- kaolinite – infilling pore spaces?
- rare heavy minerals – zircon

Texture
- generally not as well rounded or well sorted as distributary channel facies
- some grains sutured together – less porosity, but still relatively okay
- leached quartz grains
- little organic material

Comments

RE-MAC-AK15

Cement
- silica

Mineralogy
- monocrystalline quartz
- few chert grains
- rare heavy minerals – zircon

Texture
- very coarse (relative to channel facies)
- appears to be bimodal
- little organic material
- quartz overgrowths present

Comments

RE-MAC-AK16a

Cement
- silica

Mineralogy
- quartz
- few altered kaolinite grains
- rare heavy minerals – zircon, spinel

Texture
- well rounded
- moderately sorted, with few coarse grains

Comments

RE-MAC-AK16b

Cement
- silica

Mineralogy
- quartz
- few chert grains
- rare heavy minerals

Texture
- okay porosity
- subrounded to well rounded
- well to moderately sorted

Comments
- very little organic material

S-2 (upper 10 m of Aklavik Fm.)

Comments
- similar to swaley facies
- rare heavy minerals
- kaolinite present – infilling pore space
- mostly monocrystalline quartz
    - subrounded, equant grains
- few chert grains

1-4

Comments
- resembles Richardson Mountains Formation sands; not Aklavik Fm.
- appears to be a lot of stain (Fe??)

5-1/5-2

Comments
- somewhat similar to swaley facies
- rare feldspar
- monocrystalline quartz with some cherts
    - rounded to subrounded, well sorted
- rare heavy minerals

4-1

Comments
- very similar to Ak8

4-2

Comments
- similar to 4-1
- more less stable silicate grains (ie: cherts)
- sublitharenite

4-3

Comments
- very similar
- less silicate grains, more quartz
- appears to be more of a quartz arenite relative to 4-2

4-4

Comments
- similar to 4-3

6-1

Comments

- very well cemented, nor porosity
- possible alteration of feldspars – remaining is mostly clay with micas (muscovite?)
- rare quartz overgrowths (hard to see)
- chert grains
- muscovite crystals
- major porosity limiting factor here is compaction
    - chemical compaction = pressure solution

7-1/7-2

Comments

- very similar to AK8, but not as well sorted (this sample is from wavy bedded facies)
    - swaley facies shows best sorting (generally)
- dominantly monocrystalline quartz; few cherts
- quartz arenite, possible sublitharenite classification
- well sorted; rounded to sub-rounded
- porosity estimated at around 10%

7-3

Comments

- very similar to AK8

7-4/7-5

Comments

- slightly larger grain size; not as well sorted as 7-3

7-9

Comments

- highest concentration of heavy minerals (2-3%)
- dark stain (Fe-oxide?)

8-3/8-4/8-6/8-7/8-8

Comments

- all Richarson Mountains Formation
- key presence is amount of stain (Fe??)
- finer grained; less porosity; higher amount of silicate rock fragments
- sublitharenite

9-1/9-2/9-3

Comments
- somewhat resembles AK10
- stain similar to Richardson Mountains Fm.
- kaolinite; glauconite; feldspar (altered); silicate grains (cherts)
- well cemented – few inter-granular pores
- signs of compaction

9-9

Comments
- Aklavik sands; but more stains present than previously noted
- sublitharenite

9-11

Comments
- general "cleaning" upward in section
- slight degree of compaction
- sublitharenite

9-12

Comments
- appears more of a quartz arenite – fewer cherts
- this sample from Bug Creek – more stain present here than in equivalent facies from Martin Creek

9-13

Comments
- "dirtier" than 9-12
- kaolinite; altered silicates; cloudy-brown grains; very few feldspar grains

9-14

Comments
- much cleaner relative to 9-13
- well sorted; subrounded
- altering of cherts
- kaolinite infilling pore spaces
- minimal compaction
- similar to swaley facies – well sorted
- sublitharenite to arenite

9-15

Comments
- variable sorting – generally moderate
- sublitharenite – cherts; chalcedony; kaolinite

9-16

Comments
- moderately sorted; coarser grained than 9-15
- good porosity (10 – 12%); conductivity somewhat limited by smaller grains
- cherts – some altered; kaolinite; no feldspars observed

10-1/10-2/10-3/10-4

Comments
- similar to swaley facies, but not as rounded or as well sorted
- poor quality thin section

10-5

Comments
- coarser grain size relative to previous samples from section 10
- not as well sorted
- altered or partially dissolved silicate grains (cherts)
- some rounded grains; others angular or oblong
- no obvious partially dissolved feldspar grains
- this may be a channel sand?

10-6

Comments
- better sorting; very slight decrease in grain size relative to 10-5 (still larger than 10-4)
- laminae of finer grained, more cemented quartz grains throughout slide
- kaolinite development
- no obvious feldspars (this may distinguish channel sands from "shoreface" sands)

10-7

Comments
- generally well sorted with few larger quartz grains
- small amount of staining around some grains
- few altered silicates – cherts
- finer grain size relative to 10-6

10-8

Comments
- grain size increase – similar size to 10-5
- moderately to poorly sorted in some areas
- subrounded to subangular
- small amount of evidence for compaction
- no obvious feldspars

10-9

Comments
- similar to 10-7

10-10

Comments
- poorly sorted
- mix of quartz grains, very random orientation
- appears to be interbeds of randomly orientated grains

10-11

Comments
- return to well sorted, subrounded – subangular grains

11-1

Comments
- well sorted
- staining present
- dominantly monocrystalline quartz with very few partially dissolved feldspars and some chert grains

11-2/11-3/11-4

Comments
- very similar to 11-1, but with slightly more stain

11-5a/11-5b

Comments
- according to litholog, ,these samples are from a small channel (cut and fill structure?)
- similar to 10-8 and 10-5 samples
- somewhat similar to AK4 and AK6

11-6

Comments
- similar to 11-5, same facies
- obvious bimodal sorting

11-7/11-8

Comments
- not as well sorted as typical swaley facies
- appears more like channel sands, but not as consistently coarse
- could this be reworked channel sands?

11-9

Comments
- looks very similar to channel facies
- somewhat bimodal sorting
- appears more reworked than samples 11-5/11-6

11-12/11-13

Comments
- well sorted; equant grains

12-1

Comments
- tight, very little open pore space
- dominantly monocrystalline quartz; some kaolinite; cherts (partially dissolved); feldspars (partially dissolved); dark brown stain (??)
- partially altered cherts have a brown cloudy color under plain light
- partially dissolved grains creating limited pore space – but still poor conductivity
- looks similar to Richardson Mountains Fm.

12-2

Comments
- increase in porosity relative to 12-1 (~3-5%)
- very similar in composition to 12-1, but porosity is probably created by dissolved feldspars
- most evidence for dissolved feldspars from open pores with clay linings or remnant kaolinite
- clays have specks of high birefringence in them (mica originally?)
- looks similar to Richardson Mountains Fm.

12-3

Comments
- low porosity (like 12-1)
- partially dissolved feldspars present; altered silicates
- kaolinite
- dark stain around crystal boundaries
- sutured grains; concave-convex due to chemical compaction

12-4

Comments
- seems to show anomalously high porosity – could be a result of poor quality thin section

12-5

Comments
- very tight
- partially dissolved feldspar and cherts creating some porosity (but very limited)
- similar to 12-3
- 12-5 and previous section 12 samples best described as sublitharenites

12-8

Comments
- increase in porosity (~5%); similar to 12-2
- also becoming more arenitic
- porosity created by the dissolution of grains
- no/rare feldspar observed
- some kaolinite, and other clays present (remnant clay)
- open pores (2nd porosity) lined with dark brown (clay?) stain
- evidence of compaction

12-9

Comments
- very small increase in porosity relative to 12-8
- all section 12 samples are well sorted (reflecting wave influence)
- consistent composition

12-10

Comments
- same as 12-9
- quartz arenite

12-11

Comments
- anomalously high amount of brown stain (Fe-oxide?)

13-1

Comments
- Richardson Mountains Formation
- dark stain
- very fine grained
- porosity probably resulting from leached out feldspars (some are partially present)
    - this does not create very good porosity

13-2

Comments
- very limited porosity (~3%)

13-4

Comments
- looks very similar to Richardson Mountains Fm.
- similar composition and texture as 13-2
- sublitharenite

13-5

Comments
- similar to 13-4
- generally 2nd porosity only (and poor permeability)
- grains well cemented in most areas
- small evidence for compaction – not as significant as farther west

13-6

Comments
- still a sublitharenite – almost an arenite
- 2nd porosity, from leached grains (feldspars and cherts)
- dark stain along grain boundaries
- well cemented

JB-1

Comments
- closely resembles other Jurassic Butte sections (13-6)
- sublitharenite
- dissolved feldspars

JB-2

Comments
- probably a quartz arenite – is this because the cherts and feldspars have dissolved out (therefore diagenetically formed)
    - o 2nd porosity due to dissolution of grains
- evidence for compaction

JB-3

Comments
- similar to JB-2

JB-4

Comments
- tightly cemented
- looks more like Richardson Mountains Fm. (similar to sample 13-4)

JB-5

Comments
- slightly more porous than JB-4
- burrows = Chondrites

14-1

Comments
- very well cemented (appears to be 0% porosity)
- generally equant grains
- well sorted
- evidence for compaction
- dark stain present
- sublitharenite
- possibly Richardson Mountains Formation

14-2

Comments
- very similar to 14-1

14-3

Comments
- talus piece
- mostly dissolved chert creating secondary porosity (no feldspars observed)
- okay porosity, but poor conductivity
- dark stain around grain boundaries

14-4

Comments

- dark stain
- evidence for compaction
- porosity roughtly 2%
- possibly a low end quartz arenite – hard to determine because of dark stain
- similar composition and texture to other section 14 samples

14-5

Comments

- similar to 14-4

15-1

Comments

- kaolinite
- dominantly monocrystalline quartz
- few heavy minerals
- good porosity (~10%)
- quartz arenite
- few rock grains and cherts, which are leached
- generally well sorted, subrounded, fairly equant crystals
- some staining around grain boundaries

15-2

Comments

- few rock fragments and leached cherts
- similar to 15-1
- both inter- and intra-granular porosity
- no obvious signs of compaction
- well sorted; subrounded

15-3

Comments

- channel facies
- some clays infilling pores
- poor sorting and pores infilled with clay causing decreased porosity compared other section 15 samples

15-4

Comments

- similar to 15-3
- leached chert grains

15-5

Comments

- similar to 15-4
- quite a few oblong grains
- more cementing here than in other channel facies samples (especially of Martin Creek)

15-6

Comments

- more cemented
- some evidence for compaction
- probably equivalent to Facies I, but more cemented